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LARGE WIND ENERGY CONVERTER: GROWIAN 3 MW

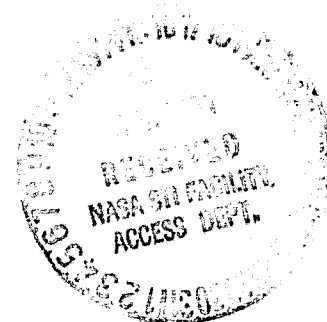
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16. Abstract This is a summarized version of the final report on the projected application of a large-scale wind turbine on the northern German coast. Details are supplied on the designs of tower, machinery housing, rotor, rotor blades accompanied by an examination of various construction materials for this unique project. A discussion is also presented on the required equipment, e.g. rotor blade adjustment devices, in addition to auxiliary and accessory equipment.					
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LARGE WIND ENERGY CONVERTER: GROWIAN 3MW
COMPLETE CONSTRUCTION DOCUMENTS FOR THE LARGE WIND CONVERTER.
FINAL REPORT

J. E. Feustel, S. Helm and F. Körber

M.A.N.

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1. Summary

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Under a contract of the KFA-Jülich Company, project management for energy research, a project group under the leadership of M.A.N.-New Technology prepared the report "Documents for Constructing a Large Wind Energy Plant Growian" from the middle of 1977 until the fall of 1978. The plant was designed as a typical individual member of a larger number of devices for providing an electrical nominal output of 3 MW to be fed directly into the main power supply in an interconnected system. A location at the northern German coast was to be employed for the plan of dimensions.

When the data for Growian are compared

- Output	3 MW
- Rotor diameter	100 m
- Height of tower	100 m

with previously constructed plants, the tremendous increase in plant size is apparent. The output in real operations did not exceed 1,00 kW, with the exception of the Smith Putnam plant. Rotor diameters were between 10 and 52 m, the towers were a maximum of 33 m in height. In Figure 1, a comparison is presented between the size of windmills and generally known buildings. From this, the dimension of the object of this project can be clearly seen. Growian almost achieved the height of the cathedral steeple in Cologne with the propeller tip, the axis of the rotor is on a level with the steeples of the cathedral in Munich. The smaller windmills in the drawing represent the American projects, the completed MOD-0A with 200 kW and MOD-2 with 2.5 MW, comparable to Growian and at similar completion times.

The task presented was successfully completed upon delivery of the documents ready for construction by M.A.N. and its subcontractors. The present concept exhibits numerous characteristics, which will have considerable significance in the area of large-scale technical utilization of wind energy. This especially applies for the interconnected system operation with commercial power supply.

The comparative consideration of other wind turbine projects, for example in the USA, demonstrates the correctness of the path taken by M.A.N. The American project MOD-2 with a wind energy converter of 2.5 MW has a centrally reinforced tubular steel tower, similar to Growian, a cradle hub and rotor blades constructed of steel. The constant development and the step-by-step construction of the American wind energy plants in increasing output stages therefore led to the present concept of very similar design features.

The deviating characteristics, such as windward rotors, no angle of flare of the blades, division of the rotor blade length into a fixed inner and an adjustable outer portion, permit interesting comparisons of the concepts and the completed plants.

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The projected wind energy plant Growian has the following main characteristics:

- The double blade rotor with cradle hub runs leeward of the tower, it is simply operated in an over critical manner.
- The machinery housing can be regulated in the azimuth position to the wind and accommodates transmission and generator as well as auxiliary equipment.
- The rotor blades have a continuous steel shaft, the aerodynamic profile is produced with glass fiber reinforced synthetic parts placed around the shaft.
- Load limitation is carried out by adjustment of rotor blades.
- Variations in rotor speed dependent on weather are compensated by the generator by means of regulating the frequency in the rotor circuit up to deviations of $\pm 15\%$, permitting direct feeding of power supply.
- The ease of maintenance and inspection is attributed to a great extent to the swivel blades at the tower (blade inspection), machinery housing on the tower which can be raised and lowered (total inspection, modification) as well as to an assembly crane in the machinery housing.

A location at the northern German coast with the prevailing wind conditions was employed as a basis for the Growian design. Calculations showed that the aerodynamic performance depends only to a limited extent on the selection of profile and blade geometry, but that the prevailing wind conditions greatly influence the energy supplied annually.

At the present time the rotor blades represent the technological core problem of a wind power plant. Additionally, testing and further optimization of the hub with the regulation of performance and emergency shutdown is necessary for economical operations on a long-term basis. The uncertainties in this area, above all with respect to the dynamic load and fatigue problems, are considerable, because the projected rotor size signifies a very large step forwards. In the present stage of development of wind energy utilization, the demands for strength and reliability of emergency systems were therefore given absolute priority for reasons of safety. This applies both to the construction of the rotor blades and to the function of the hub.

The previously mentioned aspects led to a divergence from the originally planned conception of the fiber interconnected structure in the support structure in the case of the rotor blades, agreed upon with

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the contractor. The loads occurring produced wall cross-sections, which cannot be constructed in glass fiber synthetics or in chemical fiber synthetics in controllable technology within the near future, since the dimensions achieve a multiple of composite structural parts, applied and tested up to now. Especially in the area of force conducting sections at separation points of the rotor blade, large amounts of material are necessary, requiring an elaborate construction of detail elements, a finished quality not yet achieved in these dimensions, improved resin systems, and constant fiber characteristics.

Without a doubt, the most advantageous possibilities of fiber characteristics were proven successfully in principle within the framework of the project ET 4232 A in structural part tests. The calculated values of fracture load in the static and dynamic test were virtually achieved. In a progressive program of technology, the application of fiber reinforced synthetics for structures subjected to high loads in large rotor blades should be forced.

Aspects of reliable achieveability provided the decisive factor in favor of a rotor blade with continuous steel shaft, provided with aerodynamic profile by glass fiber shape pieces. Such a rotor blade is intended for the initial plant and has been nearly completed in the meantime.

More-well founded knowledge was available for the design of the Growian tower. Numerous radio and television towers as well as water towers have previously been constructed. The moveable rotor at the top of the tower does present dynamic problems, but these can be regulated by planning adjustment dimensions in the tower and in the machinery housing. From a selection of free-standing, framework-support and stayed constructions of various heights, the optimizing process produced a cylindrical, 100 m high tower with a simple method of staying. Due to the positioning of the inherent frequency in relation to rotor rotation, this is designated as simply over critical, since the first tower bending inherent frequency is passed through when the rotor is run up to nominal speed. Special attention will have to be paid to exact investigation of ground conditions in the final choice of location, as this not only determines the stationary strength, but also the dynamic characteristics of the plant.

The machinery housing of Growian is directed toward the prevailing wind in the suspension at the top of the tower, so that the wind always flows by the rotor surface in the middle orthogonally. The structure of the machinery housing is a welded shell and it carried the rotor on the leeward side and an approx. 20 m long spur windwards. This serves for accommodating the mounting ballast when raising the machinery housing. The transmission and generator as well as auxiliary equipment are mounted in the machinery housing. An air-conditioned room accommodates the central control of the plant, while a storage room beneath is provided for the ballast for adjustment of the inherent torsion frequency. /9

The rotor hub has a pendulum joint, which is to produce compensation of the rotor blade forces in the known manner.

The performance capacity of wind is proportional to the third power of the wind speed. In heavy winds, the energy supply of the air flow exceeds the amount which the generator can assume. In order to avoid overloads, the rotor blades are adjusted in such a manner that only the energy which can be converted by the generator is taken from the wind and the short-term capacity excess remains unutilized. The adjustment of the rotor blades is carried out in Growian by electro-mechanical drives dependent upon the generator capacity.

As is the nature of wind, long and median-term variations, and also short-term variations (gusts) occur. It is the task of the blade adjustment to compensate the variations of long and median duration. The short-term changes must be compensated with a device reacting rapidly and with no inertia. For this purpose a special generator type was employed for Growian, designated as a double-fed asynchronous machine. This makes a precise maintenance of power supply frequency possible, although speed variations up to $\pm 15\%$ are permitted for the rotors of the generator. The losses for frequency adjustment are on the average of approx. 1.5% of the total electrical capacity. This converter system represents an optimal solution for wind power plant connected to a power supply, compared to the current generators otherwise applied.

The ease of inspection and maintenance of the prototype plants of a wind power plant is considered as a substantial aspect. The considerable height and relatively large mass require expensive hoists, for example when large-scale assembly work has to be carried out at the rotor. Moreover, it is doubtful whether a rotor blade at a height of 100 m can be mounted at all with justifiable work expenditure under atmospheric conditions. For these and similar reasons, a novel mounting concept was prepared. In this concept, at the construction of the tower the machinery housing is built with a free space for the tower shaft complete with the rotor and subsequently pulled to the top of the tower with built-in lifting tackle. During the lifting operation the tower passes through the machinery housing body. When required, the same equipment can be used for dismantling.

Operation of the plant is carried out automatically following a programmed schedule. The control system maintains optimal operation and simultaneously monitors the function of the components and the conditions for safe technology.

Wind turbines function virtually neutral to the environment. Taking /10 kinetic energy from natural air flow signifies no greater interference in the natural course of weather than growing a 200 m long wind protection hedge with high trees or constructing a medium multiple-story building. With the exception of a slight noise due to mechanical drives and from the air flowing around the rotor blades, there are no emissions.

The design dimensions of the plant take into consideration customary standards of machine and high-rise construction. Endangering the ground area can be controlled by appropriate safety zones, even under the assumption of higher forces.

It can be stated in summary that the proposed task of designing a 3 MW wind power plant for interconnected operation can be successfully carried out with the "documents prepared for the construction of Growian". Such a plant is technically feasible and can be produced at a price providing economical energy production, when a larger number of such power plants is involved.

Because the areas of the Federal Republic with sufficiently high wind speeds are spatially limited, however, wind energy will be able to supply only a portion of several percent of the total energy requirement. It is not in a position to replace normal power plants to a greater extent. It can, however, make a contribution as alternative energy source which is not to be disregarded, achieving approximately the capacity of the river-run plants upon completion of the project.

One solution here could be the selection of a location on the coast; in this manner this would impair neither the tidelands as biotope nor the maritime industry or persons seeking recreation. From the viewpoint of wind supply, a substantial improvement would be achieved here.

2. Introduction

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In June, 1977, M.A.N. received the order from the KFA Jülich Company, project management for energy research, to prepare "documents ready for the construction of a large wind energy plant", named Growian.

The project was awarded within the framework of the energy program of the federal government by the Federal Minister for Research and Technology.

List of Requirements

In the list of requirements of the offering for public tender the demand was made by the project management for energy research:

"The documents ready for construction must be prepared and detailed in such a manner that companies of machinery construction, electromachinery construction, construction, etc. are placed in a position to prepare binding bids with costs for constructing Growian on the basis of these documents. Moreover, it must be possible to obtain permits for construction and operation with these documents."

In addition, in the research and development contract for the project ET 4088 A one determination was made in the form of a requirement: The definition for documents for the complete construction provided under 5.1.4 of the bid is supplemented by the following addition:

"Details will be provided especially for the non-conventional parts, such as rotor blades, hub, control system, so that specialized companies not involved in planning will be

able to manufacture these plant parts without further development work. In this case the limitation applies for the composite rotor blades, that neither specifications with respect to production steps nor detailed construction drawings of production equipment are required."

Presentation of the Task

The intended aim of the project was the preparation of documents ready for construction of a plant, providing the nominal output between 2-3 MW at a wind speed of 12 m/sec or less according to the offering for public tender.

From the viewpoint of the draft, the output and the profitability, the plant should be suitable for making an appreciable contribution to the energy supply of the Federal Republic in combination with a larger number of plants.

The following requirements resulted for the general design of the wind energy plant:

- Draft as a typical single plant of a combined system.
- Direct feeding of the generated electrical energy into the existing power supply. /12
- Realizable in the foreseeable future with the application of tested technologies.

Further requirements determined were:

- Double blade rotor with cradle hub.
- Composite structure of the rotor blades.

Project Organization

The management of the project was assumed by M.A.N.-New Technology. Institutions of large-scale research and the universities, F + E - departments of the management areas in M.A.N. as well as further companies in the private sector of the economy participated in preparing the individual task packages. Figure 2 shows the project organization.

In the course of the preparation time, in some few cases it became necessary to redistribute responsibilities within the outlined organization.

Project Schedule

The time for the project was set at 12 months (July 1, 1977 - June 30, 1978). The schedule of work is presented in Figure 2. The

order was finally extended by 3 months up to September 30, 1978.

According to the definition of the concept, the technical preparation of the partial systems and the combination of these to the total plant was undertaken. The project work was completed with the delivery of 2 sets of specifications and drawings to the KFA Jülich at the beginning of July and further 15 sets at the beginning of November in 1978.

The present final report represents the conclusion of the contract work.

Representation of Results

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The results of the project are expressed in the specifications and drawings. One set of these documents comprises 86 specifications with a total of approx. 1,400 pages and about 150 drawings.

This final report presents a compact survey on the project work and points the way to the chosen solution.

There are internal final reports and accompanying written documents on a number of partial areas, listed in the appendix.

3. Total Concept

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The large wind energy plant (grosse Windenergieanlage) GROWIAN serves for producing electrical energy from natural energy of the air. A two blade rotor mounted on a tower is set into rotation by the wind and in turn drives a generator via a transmission. The electrical energy produced is directly fed into the existing power supply.

In the design, a location of the plant on the northern German coast was taken as a basis.

Above all the concept of the quantities for the wind energy plant GROWIAN takes into consideration the decisive factors for profitable utilization. The most important design criteria are:

- High efficiency (ratio of energy yield to the construction costs)
- High availability of the capacity
- Possibility for flexible operation
- Long life span (20 years)
- Easy of maintenance
- Protection against destruction in extreme situations
- Optically pleasant design

The size of the plant was not at first fixed, but a wind energy plant in the MW capacity range was required with a clearly defined list of requirements in the offering for public tender of the project management energy research on capacity, concept, components, generator and transmission. The plant was to operate on the basis of cost minimization. In the preparation of documents for the complete construction, the following conditions were to be given special attention and documented:

1. The value in the interval between 2 and 3 MW was chosen as nominal output, with which the least specific plant costs arise. Components available on the market were to be provided, as well as the possibility for mass production. After the first presentation in November of 1977, a 100 m high tower and 3 MW plant output were defined.
2. The plant was to be designed for automatic operation with a minimum of maintenance and long life span. The structural equipment was to have a long life and remain maintenance-free for the longest possible time, also taking into consideration the locations near the coast. /15
3. The duration of utilizing the nominal load and the costs for generating current are to be calculated.

Main Characteristics

The plant exhibits the following main characteristics:

- Low area load, utilization of even slight wind speeds (large rotor blade length)
- Two-blade rotor with cradle hub
- Arrangement of the rotor on the lee side
- Rotor blades with pressure point-resistant laminar sections
- Construction method of blade: steel shaft blade with glass fiber reinforced synthetic material sections
- Mechanical emergency switch-off controlled by centrifugal force
- Stable rotor blade arrangement
- Capacity regulation through blade adjustment
- Controlled setting with the wind direction
- Maintenance of the power system frequency in the case of deviations from the nominal speed up to $\pm 15\%$
- Electrical, programmed regulation and control

- Machinery housing with the rotor to be raised on the tower (assembly on the ground)
- Simple steps for the tower with one times the over critical operation
- Slender cylindrical tower shaft with constant wall thickness
- Blades which can be pivoted for maintenance on the tower

System Data

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- Rotor output	3.4 MW
- Electrical nominal output	3 MW
- Generator speed	1500 min ⁻¹ 15%
- Average annual energy yield	12 GWh
- Specific surface output	380 W/m ²
- Nominal wind speed	12 m/sec ¹
- Average wind speed (annual average)	6 m/sec (at a height of 10 m)
- Starting wind speed	6.1 m/sec ¹
- Maximum operating speed	24 m/sec ¹
- Maximum capacity coefficient	0.45
- High speed number at nominal wind speed	8
- Nominal rotor speed	18.5 min ⁻¹ 15%
- Rotor diameter	100.4 m
- Circular area of rotor	7,900 m ²
- Height of hub over the ground	100 m
- Mass of machinery housing including the rotor	242 t
- Total mass of the reinforced concrete tower	1170 t
- Total mass of the steel tower	745 t

¹Measured at hub height.

- Size of property for the operation 800 m²
- Machinery housing including the rotor/
circular area of the rotor 31 kg/m²
- Mass of machinery housing including the
rotor/nominal output 81 kg/kW

The Wind Energy Plant in a Combined Network

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Due to the nature of wind energy, the electric utility operating the plant must deal with an uncertain and varying supply for the wind-mill. Wind energy plants can therefore only participate in the entire energy production to the degree that unfavorable effects are kept within limits.

The generator design provided for GROWIAN, a doubly fed asynchronous machine, substantially meets the demands of the electric utility. In the selection of location, however, a stabilized 110 kV should be sufficiently close.

The construction of entire banks of wind energy converters (WEK) appears possible. The output of a bank, however, will be so great that variations may not only extend to the entire interconnected system. The application of WEK banks can therefore never be the undertaking of one electric utility, but rather it requires the cooperation of the combined system partners in this case to provide compensation possibilities.

Profitability

In order to evaluate the profitability of a large wind energy plant, it is compared with normal power plants. The determination of specific construction expenditures for investments for the wind power plant depends on numerous parameters of the location: the consumer and generator structure of the electric utility, the future price development in the fuel market and experience in the test operation of GROWIAN. In this case the calculations are based on a partial amount of construction costs in the form of costs saved on fuel and a partial amount due to output savings in conventional power plants. Figure 3 shows diagrams for profitability considerations.

At 4,000 operation hours and a 5% annual increase in fuel costs, invested construction expenditures of 3,350 DM per kW result on the cost basis of 1978 with a life span of 20 years. When the increase in oil price (1978-1979 approx. +85%) which has occurred in the meantime is taken into consideration and an annual price increase of 5% is assumed for the coming years, the resulting construction expenditures amount to 5,517 DM/kW.

The following goal should be examined as a result of the possibility calculations for the coming development:

- specific construction expenditures of a maximum of approx. 5,500 DM/kW

- life span of approx. 20 years
- utilization 3,500 - 4,000 hours per year
- technical availability 90% (corresponding to conventional power plants)
- specific incidental expenditures (personnel, insurance, maintenance) not higher than in the case of conventional power plants

When these development goals are achieved, a profitable application /18 of large wind energy plants appears possible within the foreseeable future with favorably structured electrical utilities and suitable locations. A prerequisite is, however, that several hundred plants are completed in order to reduce the production costs to the necessary level through rationalization measures.

Since the availability of wind energy greatly depends upon weather, the effect of fuel cost savings dominates. The effective invested construction expenditures will therefore be distinctly determined by the expected fuel price. Moreover, the necessity of saving on fossil fuels must be considered, independent of price situation. Petroleum represents especially a raw material of only limited supply, necessary for a range of products in the chemical industry. This aspect of raw material savings makes a still higher estimation of the above-mentioned construction expenditures appear justified.

Construction Costs

The costs for constructing the GROWIAN prototype will exceed the goal of 5,500 DM/kW (= total costs of 16.5 million). On the one hand, the prototype must carry the cost for the test phase (e.g. measurement towers), on the other hand the adjustment to a location and still necessary system work are included in the calculations.

In constructing a series of plants in the second generation of at least 100 wind power plants, however, the specific costs will be substantially reduced:

- The effect of rationalization in customary steel and machinery construction can be set at 25%.
- Experience with the application of new technology and additional rationalization measures will probably reduce the cost of the specific structure parts by approx. 30% or more (e.g. rotor blades).
- The less costly cement construction will be utilized for the tower.
- A learning process will also be initiated with the first plants, probably leading to simplified solutions and to less costly design (perhaps the cradle hub, blade adjustment, etc.).

On the whole it can be assumed that the above-mentioned costs per installed kW are thoroughly achievable.

In addition to the plant construction costs, the operating costs of the wind energy plant determine the work price of the wind current. For large-scale plants, numbers of sufficient reliability are not yet presently available. The determination of such numbers must be put off until after several years of operation. As far as can be seen now, these should remain within the frame of customary costs for power plants.

A more precise profitability calculation will treat the subject in more detail.

4. Design

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Three main goals are determining factors in the design of a rotor for a large wind energy plant:

- aerodynamic performance
- strength and rigidity
- production costs

According to whether the main emphasis is placed more or less on one or the other goal, differing concepts result. There is no compromise, representing a universally valid optimum. It must be taken into consideration in this case that the priorities must be seen against the background of present technical knowledge.

Philosophy of the Draft

Aerodynamic performance:

The aerodynamic performance of a chosen motor design can be calculated relatively precisely with the known methods. It is demonstrated in this case that the sensitivity of energy production in a wind energy plant is limited with respect to the aerodynamic characteristics of the rotor. Different aerodynamic profiles or blade geometries have merely a light effect on the annual energy supplied, insofar as the choice is somewhat fitting. Instead, these are determined to a greater extent by other parameters.

Strength and safety:

The strength and rigidity of the rotor blades, i.e. the insurance that the wind power plant can withstand all stresses represents the core problem in technology today. The uncertainties in this area, above all with respect to dynamic stresses and fatigue problems, are still considerable today in the stage of the projects for large plants. This is chiefly due to the fact that the rotor size projected in this case signifies a very large step forwards in comparison to the largest plant realized up to today.

In the present stage of development, the demands for strength must be given priority for reasons of safety. This applies both to the

geometry and the construction of the rotor blades and to the function of the hub.

Production costs:

While the problem of sufficient strength is to be seen primarily under the aspect of development risk in realizing a prototype plant, the problem of production costs is presented with respect to the profitable utilization of wind energy. These are determined to a considerable percentage by the costs for the rotor, especially for the blades. If the rotor blades were to be manufactured in aeronautic technology, i.e. /20 as the wings of present day large aircraft, profitability of the plant would scarcely be achievable with the connected costs, unless the production numbers are extremely large.

The rotor blades must therefore have prerequisites for low production costs, based both on the static and constructive concept and on the material selection.

The rotor design determines the following GROWIAN characteristics:

two blade rotor with lee-side design

The leeward arrangement was preferred essentially for two reasons:

- This arrangement is stable with respect to tracking the wind direction for physical reasons, so that a greater certainty is achieved in this point.
- The plane of rotor rotation can be positioned more closely to the tower, so that the machinery housing design can be shortened, leading to a saving in weight.

In comparison, the disadvantages in a capacity loss of approx. 3% and a relatively slight dynamic blade stress due to the tower shadowing effect appear less important. The diameter of the rotor was defined at 100.4 m, corresponding to the design conditions.

Blade geometry with a relatively large thickness

The application of special laminar profiles permits the realization of relatively thick rotor blades, accommodating the demands for sufficient building height with respect to strength and rigidity while maintaining a low weight without having to accept large capacity losses with the given profile geometry.

Rotor blades with a high rigidity and low mass

The selected blade geometry permits a relatively large building height for the supporting elements of the blade structure. High rigidity is therefore attained with low mass. The inherent frequency of the rotor blades therefore is far greater than the tower inherent frequency. Dynamic interference between rotor and tower is reduced to a minimum.

Blade structural method with steel shaft and glass reinforced synthetic covering

This method of construction maintains the development risk and the production costs at the lowest possible level with the present knowledge in technology. The production of such rotor blades is therefore not connected to the availability of equipment in the aeronautic industry.

Cradle hub

Among the applicable hub concepts, the cradle hub represents a good compromise solution. For small wind power plants of 100 kW, this structural method has already been proven in operation.

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Aerodynamic Design

The aerodynamic rotor blade design for GROWIAN is dominated by the goal of finding a geometry, in which good aerodynamic performance of the rotor meets the demands for strength or rigidity to a great extent.

This is achieved primarily by the relatively large blade thickness. The blade thickness extends from approx. 35% at the root to approx. 15% at the tip. With the selected special profiles, a maximum capacity coefficient of $c_p = 0.45$ is achieved for the rotor. Comparative calculations have shown that this value is only slightly less than the values achieved with thinner profiles.

A simple, straight line limited trapezoid with an expansion ratio of $b^2/A = 18.6$ and tapering of $t_a/t_i = 0.2$ was selected. In the determination of these values, especially of the expansion ratio, extreme values were consciously disregarded in comparison to similar projects. Optimizing the twist is carried out among other things under the aspect of a relatively broad extension of the capacity effectivity in the area of the layout and of a favorable partial load effectivity.

Selection of profile

Prerequisite for the realization of rotor blades with a large thickness and good aerodynamic performance is the availability of suitable profiles.

The performance of conventional profiles - also laminar profiles of previous layout - decreases rapidly with increasing relative thickness. For this reason, profiles are provided for the GROWIAN rotor blades, developed especially for wind power rotors.

These aerodynamic profiles were designed by F. X. Wortmann for large wind rotors. These were developed with the specific objective of attaining favorable C_A and C_W values as well as a positive stalling behavior with relative thickness of 15-35% (Figure 4).

Moreover, the profiles are distinguished extensively by pressure point-resistant behavior. With this characteristic, large alterations in aerodynamic moments are avoided with respect to the required blade

adjustment angle moments. Controlling the aero-elastic influences, e.g. fluttering, is also facilitated.

Rotor blade geometry

Taking into consideration the aerodynamic, strength and constructive requirements the design of rotor blade led to a relatively slim trapezoid blade draft with the geometric dimensions described in the following. /22

nominal blade length	50.2 m
blade depth (at the root)	4.25 m
blade depth (at the tip)	1.30 m
tapering	0.32
blade surface area	135.8 m ²
wing extension	18.6
surface density	1.7%

Figure 5 shows the blade with 4 profile cross-sections.

Performance

The performance computation for GROWIAN was carried out with a computer simulation program, calculating the specific characteristic performance data of wind rotors. It applies the blade element theory with solution procedures developed by Wilson, taking into consideration losses at the blade tip and hub, determined according to the mathematical approaches developed by Prandtl or Goldstein.

Rotor performance envelop of characteristic curves

The effectivity of the aerodynamic and mechanical energy conversion of windmills is described by the performance coefficient c_p . The dependency on the rotor speed and wind speed as well as the blade adjustment angle can be represented in the form of the $c_p - \lambda$ - performance envelope of characteristic curves. The high speed number indicates the ratio of blade tip speed and wind speed in this case.

Figure 6 shows the performance envelope of characteristic curves for the GROWIAN rotor. The maximum performance coefficient is $c_p = 0.45$.

The relationship of rotor performance to speed

The relationship between rotor performance and rotor speed for various wind speeds can be seen in Figure 7. It can be seen from this that for increasing wind speeds the individual performance maximum wanders to higher speeds. An optimal utilization of wind performance could therefore be carried out with a corresponding adjustment of the rotor

speed. For plants functioning with fixed speed and synchronous generators, this is not possible. An optimal adjustment is possible in a limited range around the operating point in GROWIAN, thanks to the speed variation of the double-fed asynchronous machine.

Wind data

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For the computation of the energy generated annually by GROWIAN, the wind conditions at List on Sylt are applied, since data for this location were accessible to a sufficient extent and are approximately representative for the GROWIAN location. Figure 8 shows the correlated wind profile, representing the average annual wind speeds compared to height. At a hub height of 100 m, the 100 m long rotor covers a height range between 50 and 150 m. In this range between 50 and 150 m, the average wind velocity increases from 8.5 to 9.9 m/sec, so that the rotor is subjected to a constant alternating stress over the circumference in addition to the stochastic gust stresses.

From the meteorological data, the relative frequency of the average annual wind speeds, shown in Figure 9, can be determined. The values apply in this case for a 100 m hub height. An annual average of 9.36 m/sec results for this height over the period of one year. The most frequently occurring wind speed is situated around 7.5 m/sec.

Optimizing rotor speed

The rotor nominal output of 3.6 MW, producing the initial generator output of 3 MW when taking into consideration the mechanical and electrical conversion effectivity, is generated at differing nominal wind speeds according to the rotor speed. If the output curves for the individual speeds are now overlapped with the local wind performance spectrum, the dependency of the annual energy yield on rotor speed can be represented (Figure 10).

The computations show that the optimal rotor speed with the greatest energy yield for the location at List/Sylt is situated at 18.5 min^{-1} .

Supplied energy

The annual production of electrical energy can be determined by combining wind supply and rotor performance characteristic. The numerical evaluation using a digital computer program (EWEK) produces 11.7 GWh per year for the wind conditions at List/Sylt used as a basis.

As the performance duration line in Figure 11 demonstrates, GROWIAN will supply nominal output at 18.5 min^{-1} 22% of the year (1,957 hours), operate at partial load 55% (= 4,845 hours) and have no output 23% of the time (1,958 hours).

For the rotor nominal speed, a minimum operating wind speed of 5.3 m/sec is obtained when including the idling losses, at which the rotor can still maintain the nominal speed without losing output. The maximum operating wind speed amounts to 24 m/sec. At wind speeds above this value, the plant is dropped to zero output.

In the efforts to obtain the most precise energy yield calculation, it must be noted that the approaches taken contain a number of hypotheses founded on fundamentals, but which cannot exclude a certain scattering /24 range of the resulting numerical values. An uncertainty factor with a possible positive or negative effect is to be seen, for example, in the conversion of height of the wind speed measured at a height of 10 m to the rotor surface area extending from 50 - 150 m above the ground. The height conversion is necessary, because measurements are ordinarily made by the meteorologists at a height of 10 m. Since the third power of the wind speed is included in the performance calculation, differences can arise here rapidly.

The calculations based on the wind conditions of the location at List on Sylt will also not correspond precisely to the GROWIAN location in Kaiser-Wilhelm-Koog.

Characteristics of the completed wind power plant dependent on construction and operation (e.g. swinging of the rotor, speed variations, wind direction tracking, etc.) may also have an effect on the actual energy yield, although not as decisive as the wind conditions.

A more exact performance computation can not be undertaken until wind data are available from the plant measurements over a longer period of time at the selected location of the wind energy plant with the aid of a 100 m high mast. Finally, the system-specific effect of the plant components on the energy production is to be studied after beginning operation within the framework of the measurement program.

Load Assumptions

Definition of the load cases

The following load assumptions were employed as the basis for the design of the rotor and therefore also the resulting load for the entire plant:

Fatigue strength during entire life
Load case 1: normal operation

100% nominal speed at all wind speeds, greater than the minimum speed required for achieving the nominal speed.

Fatigue strength for alternation of load numbers $N \leq 10^4$
Load case 2: positive threshold load

100% nominal output at nominal wind speed. In a gust, the wind speed is doubled. The expected frequency is situated at 10^4 load changes. The rotor is simultaneously hit over the entire surface area. Safety factor for fatigue.

a) Assumptions on calculating the rotor blade stresses:

- The blade adjustment angle remains unaltered.

- The shape of the gust is rectangular with duration of 0.5 sec of the maximum value.

b) Assumptions on calculating dynamic processes:

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- The blade adjustment angle is altered with the quantities determined through control, such as alteration speed dependent on output and delay in response time.
- The maximum speed gradient of the forward flank of the gust amounts to 6 m/sec^2 , at the rear 1.2 m/sec^2 .

The shape of the gust can be described approximately as a trapezoid, with a 0.5 sec duration of the maximum speed value.

Load case 3: negative threshold load

100% nominal output at switch-off speed of 24 m/sec; overspeed +15%. In a gust, the wind speed drops to $0.6 \times 24 \text{ m/sec}$, no change in blade adjustment angle, rectangular gust shape. This load case serves only for calculating the blade load, frequency 10^4 load change. The rotor is hit over the entire surface area simultaneously. Protection against fatigue. Fatigue strength for load change numbers $N \leq 10^3$.

Load case 4: positive extreme gusts at +15% overspeed

100% nominal output at switch-off wind speed of 24 m/sec. In a gust, the wind speed increases to 40 m/sec. The expected frequency is at 50 load changes. The rotor is simultaneously hit over the entire surface area. Protection factor for fatigue.

a) Assumptions for calculating the rotor blade stresses:

- The blade adjustment angle remains unchanged.
- The shape of the gust is rectangular with a duration of 0.5 sec of the maximum value.

b) Assumptions for calculating dynamic processes:

- The blade adjustment angle is altered with the quantities determined by control, such as alternating speed dependent on output and delay in response time.
- The maximum speed gradient of the forward flank of the gust amounts to 8 m/sec^2 , that on the rear 1.5 m/sec^2 . The shape of the gust is approximately a trapezoid with a duration of 0.5 sec of the maximum speed value.

Load case 5: positive extreme gust at -15% minimum speed

All other definitions as in load case 4.

Load case 6: negative extreme gust

100% nominal output at +15% overspeed and 120% switch-off speed $v = 30$ m/sec. In a gust, the wind speed drops to $2/3$, no alteration in blade adjustment angle, rectangular shape of gust. This load case serves only for calculating the blade stress; frequency 50 load changes. The rotor is simultaneously hit over the entire surface area. Protection against fatigue.

Load case 7: emergency switch-off

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100% nominal output at -15% overspeed and switch-off wind speed of $v = 30$ m/sec. The blade adjustment angle is brought to the standstill flag position with the maximum permissible adjustment speed. Frequency 500 load changes, protection against fatigue.

Extreme gust cases

Load case 8: standstill

The century gusts of 60 m/sec hit the rotor blade in flag position over the entire length.

Load case 9: slowly rotating plant

The century gusts of 60 m/sec hit the rotor blade in flag position for 40 m/sec over the entire length. The rotor rotates slowly with the speed defined for the waiting position. Protection against fracture.

Load case 10: maintenance case

A rotor blade is fixed at the tower. The flow passes across it at a wind speed of 45.6 m/sec, defined by DIN (German Industrial Standards) for high-rise buildings. Protection against fracture.

Note: In comparison to the specification SS-W 705 081-001, the load cases were renumbered and the load case 10 was added. There is agreement in the subject matter.

Rotor Loads

Based on the defined load cases, the stationary rotor stresses due to wind and mass forces were determined with the aid of a digital computer program. For the computation of the course of load, a computer program was applied, first developed by the DFVLR for helicopter rotors and later modified for wind rotors, permitting the representation of a variety of rotor configurations and operational states through a larger selection of input parameters.

Figure 12 shows the coordinate systems and definitions of forces on which the calculations are based. For the rotor blade structure design, the blade connection forces, the tangential clamping moment and the radial distribution of forces of the air and of the moment of torsion in the rotating blade system are determined, also taking into consideration the inertial forces originating from the swinging motion. The non-rotating

rotor midpoint system serves for representing the overlapping rotor stresses, which must be assumed by the subsequent plant components, such as rotor shaft, transmission, generator and tower structure. /27

Several results of load case calculations for a rotor of the project GROWIAN are shown in the Figures 13 to 14.

In Figure 13, the course of important force components is compared to the rotor angle of rotation, clearly showing the influence of a gust (corresponding to the definition of load case 2).

With the evaluation of the load peaks during the gusts in the form of the blade bending moments in the impact and pivot direction for two different load cases (Figure 13), the basic data for dimensioning the rotor blade structure are obtained. Comparative load case calculations with variation in geometric and kinematic parameters serve for optimizing the rotor design.

In Figure 14, the influence of the angle of flare on the load average values and amplitudes is shown.

The blade angle return control contributes to the reduction of rotor impact motion and therefore load variations of several components, as can be seen in Figure 14.

Structure Computation

Studies on structural mechanics were carried out in virtually all supporting components of the plants. They provide information on shaping, stresses and inherent vibrations of the structural parts.

The building regulations employed in this case are of decisive significance for the structural safety of the structural elements. In these regulations the permissible stress values for the material and the connection elements (above all for welding seams) are determined, independent of the type of stress occurring. In this case it must first be determined whether there are not yet any special agreements for wind power plants. This would provide considerable room for judgment on the part of the construction engineer, concerning which available DIN standards or other building regulations, e.g. from aeronautics, are employed for orientation purposes.

Since a portion of the plant components is a normal high-rise building (tower) and ordinary machinery construction (machinery housing, hub), the final report essentially treats only non-conventional structures. These are component parts of the rotor blades, which have not been realized in these dimensions up to now.

The calculation of the blade shaping, stress distribution and inherent vibrations are the basis for the study of the system dynamics and the strength and construction design of the blade. The rotor blade represents a structure with a substantially greater length than the cross-sectional dimension. It can therefore be treated as a rod under stress due to external and inertial forces. In the area of the connections, however, this idealization is insufficient. In this case /28

calculations were carried out according to the method of finite elements.

The work on clarifying the structural mechanics of the steel structural parts of the rotor blade employed the versions of rotor blades with a 12/15 m long and alternatively with 30/32 m long steel shaft. The methods employed are based on idealizing the supporting structure as a beam with multiple-celled hollow cross-sections. In this case various shapes of shaft casing and differing designs of the crosspieces as skeleton structure, entire wall and wall with holes were studied. A simplification was introduced for the inner blade portion with respect to distribution of mass insofar as an even distribution of mass was assumed. Only slight errors in the inherent frequency of torsion vibrations result due to the simplification.

Two variants with differing course of wall thickness were defined for the steel shaft blade up to 30/32 m. The first variation provides no individual direct-access flange, while variation 2 has two individual flanges.

Three load cases were taken into consideration at first for determining the stresses and shaping for the dimensions:

Normal operation

Positive threshold load (wind speed 12 m/sec - 24 m/sec)

Positive extreme gusts

The blade is divided into short sections for the stress computation, assuming cross-sectional size as constant. The profile cross-section is divided into flanges and walls.

Survey of the results

The results are available in a variety of computer print-outs and graphs. Figure 15 representatively shows the distribution of the longitudinal flow of force and the flow of thrust in a shaft cross-section.

The evaluation of calculations produced the result that the inner blade area (6 to 15 m) is not problematical. Compared to the calculated configuration, however, the thrust midpoint must be repositioned due to a heavy crosspiece design, so that the transverse force torsion is negligible. In the area of 15 to 30 m, corresponding cross-sectional reinforcements must be undertaken in order to achieve the required protection.

In Figure 16 a table shows the calculated inherent frequencies of the rotor blade in the steel compound structural manner. The vibration forms of impact bending, pivot bending and torsion always occur in pairs. The dominating shaping type is indicated in the column "form".

The illustrated calculations were carried out in parallel for the two variants with differing compound material portion. /29

Vibration Behavior

The dynamic behavior of a wind energy plant as total system can be deduced with the aid of suitable coupling procedures from the behavior of the partial systems, such as rotor, machinery housing and power. The question of rotor model had to be treated and the interaction of the low-frequency tower vibrations with the swinging motion of the rotor had to be examined. Moreover, the interaction of the effective power and speed regulation with the mechanical degrees of freedom for the entire system was clarified under the assumptions made.

The projected wind energy plant GROWIAN has no model based on type and especially on absolute size. The uncertainty therefore remaining in the statements based on the model employed for assessing the entire dynamics must be accepted at present.

Studies of the rotor components show that impact has the lowest frequency of the three elastic degrees of the blade, i.e. impact, pivot and torsion. In addition to ensuring the flutter stability, above all the question has been approached within the framework of the entire dynamics, to what degree an elastic model of the impact motion is required. The individual considerations on elastic blade impacts show that the basic impact bending is dampened to an extreme degree by the forces of the air. It therefore follows that virtually no dynamic excesses are created in stochastic wind excitation, so that assumptions can be based on a quasi-static blade shaping. In suppressing the elastic impact motion, the forces transmitted from the rotor to the machinery housing are accurately reproduced to a great extent as is the radial distribution of force over the wing.

The analysis of the effect of individual disruptions (monthly gusts at operating speed, yearly gusts with rotor in a transverse position) shows that with increasing rising wind the dynamic coefficients of increase also increase, especially at the wing tips. This result is understandable, since a maximum dynamic increase is expected for an impulse-shaped load of one-half the duration of periods of the blade impact motion.

Of the various types of stress, the case of the blade passing through the tower shadow most closely approximates this condition, with the largest dynamic increases occurring. A study of the entire dynamics of GROWIAN with fixed rotor blades is therefore the worst for acquiring data on this case; the planned evaluation of observations must take this into special consideration. /30

Preparing a comprehensive calculation model for the entire system of GROWIAN with all the parameters essential for dynamic behavior is an exceptionally extensive task. Therefore a simplified whirl-flutter calculation model was first employed for the study of stability. It has a fixed rotor with impact motion defined by the position of the blade tip plane in space. The movements of the tower are characterized by two bending motions perpendicular to one another and a torsion. The application of rotor coordinates rotating with the system is paramount to a study with parameters averaged in time of the periodical system of a two-blade

rotor with unsymmetrical support. The study of stability is therefore especially easy to survey, but is not complete with respect to parameter-generated vibrations. In this case both the first two basic bendings and the torsion as well as the two following top bendings and torsion are taken into consideration. The blade angle return control was varied as parameter. No case of instability resulted for the design of GROWIAN. Generally, the tower movement was dampened by the rotating rotor, more greatly with increasing blade angle return control. Simultaneously, however, dampening of rotor motion was reduced.

The possibility of parameter-generated vibrations of the entire system under the influence of gravity was studied with a further calculation model. No case of instability of this type resulted due to the very high pivot and bending frequency.

A refined computation model was defined for more precise stability studies and problems of the dynamic response of the entire system. The complete compilation of motion equations is achieved by symbolic programming. The inherent vibration forms of the tower and the rotor blade serve as degrees of freedom in this model. The gondola azimuth, rotor position and collective adjustment angle of the blades are considered as randomly dependent on time for a wide applicability of this model. The various construction possibilities in the pendulum hub design are taken into consideration to the greatest extent. As a model fitted to the present GROWIAN draft, the equations are reduced to an elastic tower, modally represented with five inherent vibrations and a fixed swinging pair of blades with impact angle return control due to the high blade inherent frequencies. In this case, the forces in the air are dependent on the system motion and on time. The study of stability is carried out with the aid of the Floquet theory for linear differential equation systems with periodic coefficients.

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Results were gained, comprising the dynamic stability in the operating range and a study of parameters for the degree of pendulum freedom. Within the framework of validity limits of the present computer model, it can be concluded that the behavior of the entire system in GROWIAN is stable. In this model a fixed rotor and constant rotor speed are assumed.

Coupling the effective output and speed regulations with essentially mechanical degrees of freedom produces a simulated model for conducting transient studies. Stochastic variations in wind and load drops are among the examined load cases. The simplified selected data provide no suggestions leading to induced vibrations and instabilities through the interaction of control and dynamics. The expected vibrations of the tower model do occur in the case of load decrease, but they disappear again.

On the basis of the present studies it can be stated that from the viewpoint of dynamics no danger is produced, putting the entire system of GROWIAN fundamentally in question.

Control

In the preparation of the control and regulation concept, the assumption was made that GROWIAN functions completely automatically, monitored only from a system dispatching center. The system dispatching center receives only collected disturbance report, position indications of the middle voltage switch and data on output and voltage of the machinery. Output and voltage can be influenced by the system dispatching center, but beyond this function, only emergency switch-off is possible from the dispatching center.

The appropriate equipment is present in the control room of the machinery housing for commencing mechanical operations in order to carry out testing and maintenance, without accessibility, however, to the control of the power portion of the plant. In the control room of the switchhouse at the base of the tower, all monitoring systems converge, so that the plant can be operated manually or automatically from this point.

In normal operations, actual control is carried out by the automatic system. This operates the plant in conjunction with commands of the system dispatching center when wind is sufficient, maintains nominal operation, switches to waiting position or stops the equipment. The transition from one operating state to the others is also carried out automatically upon demand, as is disruption of operation in case of danger.

Regulation of output and speed

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In the regulation of output and speed of the plant, two differing operating modes are differentiated according to the available wind speed:

Partial load range

- At a nominal wind speed of less than 12 m/sec, the output of the generator is regulated by altering the rotor current in such a manner that the nominal speed is maintained.

Full load range

- At wind speeds greater than the nominal wind speed of 12 m/sec, the regulating system triggers the rotor blade adjustment and maintains constant speed at nominal output of the generator by causing the rotor to accept wind energy only to the required extent by blade angle regulation.

In the partial load range, the generator output is less than the nominal output of 3 MW. In order to utilize the complete available wind capacity, the generator moment is regulated by a constantly maintained, optimal position of the rotor blades in such a manner that the speed remains exactly equal to the prescribed speed. This operational mode is employed at wind speeds between 5.5 and 12 m/sec.

The generator output is greater than 3 MW at speeds greater than 12 m/sec. In practical operations this transition point, at which exactly the nominal output is generated, may shift slightly. The higher output is not accepted by the generator, it operates at the constant full load of 3 MW. The excess wind capacity can by-pass the windmill so to speak due to regulated adjustment of the rotor blades.

Azimuth regulation

Regulation of the azimuth must fulfill the task of guiding the rotating machinery housing with the direction of the wind. The wind direction is transmitted by the wind measurement equipment in the form of an average value over a defined period of time to the regulating system and this compares the value with the actual angle of the machinery housing. The guiding unit guides the machinery housing to the direction of the wind when a defined deviation is exceeded.

Automatic system

All above-mentioned elements for control and regulation of the wind power plant are combined in the so-called automatic system. This is divided into the subautomatic systems of the individual operating groups and in superordinated control automatic system of the entire machinery set. Supplementing the automatic system, elements for monitoring the plant and ensuring optimal operation also become active.

The totality of the organs for operations is designated as "operational logic".

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5. Design of the Plant

Tower

The GROWIAN tower must fulfill, above all, two tasks:

- It supports the machinery housing and the rotor and conducts the operating forces away.
- It provides access to the head section.

Moreover, the tower construction, together with the rotor and the machinery housing, must ensure optimal operation of the plant. This requires, above all, special rigidity and vibration characteristics.

The final solution is characterized by several parameters:

- hub height
- material
- inherent frequency
- support system
- cost

The inherent frequency requirements prove to be the most important and most difficult points of the study. The absolute value of the inherent frequency, the inherent shapes and the correlated cutting forces exert substantial influence on the selection of tower. Therefore extensive calculations had to be carried out.

In principle, all normal systems in tower construction were taken into consideration. On the basis of financial, constructive, aesthetic and other reasons, however, many were already rejected in the early stages. For the final selection the following types remained

- free-standing towers
 - towers with single stays
 - towers with double stays
 - towers with triple legs
- (Figure 17)

In the selection process, the group of the "simple over critical operated towers" had decisive advantages, especially of a financial type. The designation "simple over critical" signifies that the first bending inherent frequency of the tower must be driven through upon running of the plant with increasing rotor speed. Well-founded calculations, however, proved the definite controllability of this passage resonance, to that it provides no danger for the entire plant.

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The process of finding an optimal solution therefore produced a 100 m high, cylindrical tower with single guidelines as the best solution. The shaft is manufactured either of steel or reinforced concrete. The stays can be decoupled during plant maintenance and lowered with the machinery housing.

Variant of the Tower in Reinforced Concrete

The prepared tower construction is presented in the following and the most important structural characteristics are explained briefly. See also Figure 18.

Tower foundation

For a normal building site, a circular plate foundation with a thickness decreasing toward the edge is provided. The outside diameter amounts to 13 m. The chosen cement quality is B 35 with special characteristics to compensate for the detrimental effect of the ground water. The middle section of the foundation is not on a hollow support, deviating from the generally customary design.

Tower shaft

The shaft is cylindrical with a circular cross-section of 3.5 m outer diameter and 0.25 m wall thickness. B 35 was chosen as cement quality, since it has special characteristics to deal with weak forces of the air. In the upper tower section above the guideline connection, the shaft is vertically prestressed. The tower is to be constructed in climbing form technology or sliding form technology in two stages.

In the connection to the head, a special elastic torsion support will be installed.

Installations in the tower shaft

The interior is utilized completely. Access to a light steel staircase, a climbing elevator and several cable shafts is provided by a door at the tower base. In the interior of the shaft there are also the adjustment weights, aiding in the rough or fine adjustment of the tower inherent frequencies. Furthermore, idler and guide pulleys are installed for the lifting cables of the machinery housing.

Foundations for the guidelines

The ground water conditions will probably require a foundation anchored deep in the ground. One clamp each is fixed on the foundations, on which the guide cables are connected and prestressed.

Double guide cables

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These connect the upper tower portion with the guide foundations. The cross-section is large and provided with special protection against corrosion. The connection to the shaft is carried out by means of a steel ring, which can be lowered together with the head portion for maintenance. The prestress forces of the cables are relatively high; they are never completely free of a load, even one-sided with extreme bending load.

Variant of the Tower in Steel

Tower foundation

Deviating from the solution with reinforced concrete, the foundation has a hollow support in the middle section. The outside diameter is increased to 14 m. The tower shaft is connected by short tension elements and foundation.

Tower shaft

The cylindrical shaft of 3.5 m outside diameter is constructed of 9 m long tubular sections, already provided with the fixed installations to a great extent at the plant.

In the lower tower element with a wall thickness of 25 mm, the entry door is +3.1 m above the upper edge of terrace, reached via an outside staircase.

In addition to the base element of the tower, the stay area at the top of the tower have a wall thickness of 25 mm; the standard thickness of the tower walls amounts to 18 mm in the other areas.

The headring of the tower forms the upper connection of the tower. It is connected with the azimuth support ring via support bars and is designed in such a manner that the assembly lifting equipment for the machinery housing can be attached at this point. The assembly lifting equipment is identical for the two tower variants.

With in this area, the tower is protected by a "staircase", preventing the occurrence of a chimney effect.

Installations and guide cables with foundations correspond to those of the reinforced concrete tower. The dimensions of the guidelines, however, are about half as large for the steel tower because of the reduced prestressing.

Comparison of the two tower variants

Both tower variants ensure the function to the same degree and have correction possibilities for fine adjustment of the vibration behavior. The reinforced concrete tower is less expensive, above all, for individual constructions, for which there is no rationalization effect possible in steel construction. For the prototype of the plant, however, greater adjustments in vibration behavior, as well as the calculated costs for disassembly, may have to be considered. The steel tower has the greater room for adjustment, specifically with respect to possibly required, additional installations. /36

Adjustment to conditions of location

The individual construction site characteristics have a determining effect on the foundation. In certain cases, they may also have an unfavorable effect on the cable inherent frequencies, thereby requiring multiple subsequent corrections. The possibility for correction is provided.

Very weak ground can also have an influence on the dynamic design. An adjustment of the concept then becomes necessary.

Machinery Housing

The machinery housing has the task of transmitting the reaction forces from the rotor to the tower head and of adjusting the position of the rotor to the individual wind direction via the rotating support.

Furthermore, it accommodates the machine equipment of the plant, such as transmission, generator, central control system and further auxiliary aggregates (Figure 19).

The preliminary draft breaks up the support construction into a skeleton structure with the external shape provided by a light covering. In the course of the development it proved to be advantageous to convert to a supporting, rigid horizontal tubular casing, accommodating all loads from weight and operating loads (Figure 20). With this manner of construction, an optimal amount of space is achieved for the machinery housing size with good rigidity, dispensing with a covering. The tubular casing (diameter 6 m) carries the forces in the tower via a vertical center tubular section (diameter 5.1 m) and the following support construction.

The machinery housing collar is adapted to the diameter of the vertical cylinder beneath the support ring. Its task consists in

transmitting the machinery housing bearing forces to the tower during assembly. The collar accommodates the lower 3 cable pulley packages of the assembly lifting equipment and the guide pulleys. The machinery housing is support symmetrically during assembly by the cable pulley packages.

The entire hub complex, including rotor and transmission, is connected to the projecting rigid hub support tubular section of the machinery housing area by the casing of the external support ring. This tubular section is supported on the circular ring disc of the horizontal support cylinder and is held at the end on the vertical cylinder.

The support structure of the rear section is designed for the assembly suspended on the cross-arm - compensating ballast.

The cross-arm is shaped as a tapered tubular section with a track set into the lower side for the moveable wind measurement instruments. The wind measurement equipment is fixed on a mounting, moveable on the entire approx. 20 m long cross-arm.

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In addition, a maintenance gondola can be suspended in the guide tracks for inspecting the entire cross-arm from the outside and for correcting defects in the wind measurement equipment while in position.

The required assembly hatches, the ballast chambers for the vibration compensation ballast and the insulated control chamber are in the rear section. One of the most important demands for the insulation of the control chamber is a completely vapor-tight and inflammable design.

For the separate generator installation and removal, a cable pulley is installed over the lower assembly hatch. This hatch is closed by a mechanically closeable double-wing flap. The flaps are locked in the closed position.

In the middle section of the machinery housing, a telescope derrick is installed on a special platform for purposes of inspection and maintenance. The platform also serves as supporting disc, since the form construction of the machinery housing is interrupted at this point by the derrick hatch. Due to lack of space, the telescope derrick cannot be completely accommodated in the machinery housing; in the upper section, it is integrated in the machinery housing with an aluminum covering.

There is an opening of 6.5 m length and 4.8 m width above the derrick in the covering. The hatch is closed by means of a "skylight-sliding roof". The sliding roof consists in four parts, supported at the front in the guide tracks.

For a precise mounting of the generator in the final state, a carrier sliding railway is installed. On these support, situated on an inclined plane, the generator slides into the final position without the necessity of subsequent position correction. The supports of the sliding railway can be shifted in a lateral direction in the area of the lower assembly hatch in the rear section and can be dismantled in the tower area.

The support of the generator is carried out at four points on springs for vibration insulation. The air cooler is positioned on the generator

with inlet and outlet openings in the aluminum covering outside of the supporting construction.

The main walkway is a platform at a height of +100.0 m, extending from the air-conditioned control room to the hub area. The entire walkway of the machinery housing (platform, ladder, terrace) is generally designed of aluminum in order to reduce the machinery housing weight and to facilitate removal of parts which can be disassembled. The parts which can be dismantled are situated in the tower and generator installation and dismantling area.

At the front of the hub support tubular section, the rotor support is mounted. This fulfills the task of assuming all dynamic and static loads of the rotor. /38

The azimuth support represents a connection between the stationary tower and the rotating machinery housing, designed as single-bearing construction and transmitting all occurring forces from the machinery house to the tower. The bearing is intended for the first installation as undivided bearing. The outer ring of the bearing carries a gearing, in which the pinion of the transmission and the interlocking contacts of the wind direction guide mesh.

Producing the machinery housing at the plant is carried out in the largest possible pieces, according to the transport possibilities to the construction site. The final assembly at the construction site is carried out with few assembly welded seams. If transport on a ship from the plant to the construction location is possible, the low-cost and precise construction can be undertaken to a great extent at the factory.

Machinery Equipment

Under the heading machinery equipment, the structural parts of the plant are examined, serving the mechanical output transmission between rotor and generator. Furthermore, auxiliary equipment is explained (see also Figure 18).

Transmission

The relatively low rotor speed of large dimensioned wind turbines requires a high-ratio transmission to provide a useable initial speed for normal generators. In the present case a ratio of 1:81 is necessary in order to reach 1,500 rotations per minute of the generator rotor from the rotor speed of 18.5 min^{-1} .

A solution initially studied with a spur gearing had to be rejected due to the high weight in favor of planetary gearing. An adjustment to alterations in rotor speed is possible by means of a subsequent spur gearing stage.

Brakes

In the original concept, disc brakes at the transmission exit were planned to hold the rotor at a standstill. For this purpose, a relatively small single disc brake was sufficient. Progress in preparing the wind

power project then made it appear appropriate to let the rotor brake participate actively in the course of operations, especially to apply them in emergency actions in the case of threatening overspeed.

The resulting problem was characterized less by a required braking moment than by the limited heat capacity of the brake disc. Therefore a multiple disc brake is planned with sufficient capacity for braking the rotor.

Cardan shaft

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In the further course of the flow of force there is a cardan shaft, producing the connection to the generator shaft. This compensates for any errors in alignment between the transmission exit and generator.

A gear-shift clutch between transmission and generator was not planned, since there appeared to be no necessity for this.

Wind direction guide

Wind turbines with a horizontal rotor axis require a system guiding them with the altering wind direction, in contrast to vertical axis machines.

Leeward rotors have the tendency to stabilize automatically in the wind, similar to a wind vane; however, a controlled wind direction guidance system is necessary for a large-scale plant.

A special drive is planned for stable operation of GROWIAN, meshing with two pinions in a spur wheel mounted to the tower. Two motors of redundant function are available.

The double equipment was selected, because turning the rotor from the wind by pivoting the machinery housing up to 90° with respect to wind direction is a component part of the safety concept.

In the case of a power outage, the machinery housing is automatically positioned into the wind in a braked rotation.

Further auxiliary equipment

A number of auxiliary devices is necessary for operating the plant. This includes lubricating oil supply, heating, cooling aggregates and the central control room in the machinery housing, technical measurement supervision of the machines and maintenance equipment. The final report does not expand on this customary equipment of technical plants, since these are not specific to wind power plants.

Rotor

Hub

The structural shape of the hub was defined to a great extent by the

task of the project. According to this, the cradle hub tested only in smaller plants was to be employed. The purpose of the cradle hub is to compensate for unequal wind forces at the rotor blades within the rotor and therefore reduce the load on the entire plant.

Furthermore, the hub concept was determined by the rotor and blade support, the mechanism of the blade angle adjustment, the emergency stopping equipment and aspects of assembly and maintenance. In the design dimensions of the hub, the requirements for rigidity of the entire construction had to be included in the approach in addition to the stress on strength.

The construction resulting at the conclusion of the project represents a parallelepiped-shaped frame in a simplification with one rotor blade each connected at the narrow sides. The pendulum axis is arranged at the center of gravity of this shape, around which the frame including blades can swing in the direction of blade rotation. The transition to the rotor bearing is produced by the so-called traverse. The T-shape construction accommodates the pendulum axis in the cross beam of the T, while the perpendicular beam represents the rotor axis and is constructed as a tubular section. See Figure 21 for the representation of concepts. /40

Rotor bearings

Preliminary studies extended to the construction of bearings, size and arrangement in the center of gravity of the rotor, as well as operational safety and life span, given the installation conditions and loads. It was assumed that the bearings can be dimensioned for the entire life span of the wind power plant.

The selection process produced a pair of tapered-roller bearings, prestressed without play hydraulically in the operations. The diameter amounts to approx. 1.8 m.

Rotor blade bearings

For regulating the rotor output, the blades are adjusted around a longitudinal axis, so that the adjustment angle is altered with the relative wind direction and therefore the profile uplift. The selection of rotor blade bearings presented construction and calculation with special tasks. The demand, on the one hand to accommodate considerable forces and moments from the blades, and on the other hand to ensure the least possible bearing friction and long life span, led to various solution proposals in the course of processing.

At first, a hinge-type bearing was examined, but this led to a very wide hub in the area of the axis and to an unfavorable flow of force at the root of the blade. The finally selected solution employs a pivot per blade, accommodated in a bearing seat of the pendulum frame. On the basis of the large forces exerted on the rotor blade, the bearing diameter of 3.6 m had to be selected.

Blade adjustment direction

The blades are turned on a longitudinal axis to run up and stop the plant and to regulate the rotor output, thereby altering the relative angle of the air.

From the broad range of mechanical, electrical and hydraulic drive possibilities and their combinations, a solution with electrical drive and mechanical power transmission was selected. An electromotor positioned centrally on the hub is applied via distribution gears, cardan shaft and planetary roller spindles to an adjustment lever. The turning motion to be carried out extend over an angle range of approx. 90° (Figure 22).

The rotor blades are mechanically coupled with respect to angle position by the linkage of the adjustment equipment. Coupling permits compensation of unequal wind forces at the two rotor blades by opposite blade adjustment during swinging of the rotor.

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Emergency switch-off equipment

The rotor should not achieve any impermissible high speed, endangering the existence of the plant or threatening surroundings, even in the case of plant control failure.

There are two paths in principle to limit speed, either the rotor blades are prevented from accepting uncontrolled wind energy or the excess energy is removed by a brake. The available space and economic aspects led to the selection of the first path. The first path represents the more elegant and feasible solution. A brake cannot be applied to the rotor for longer periods of time.

The constructive solution of emergency switch-off equipment provides a lever action operated on centrifugal force, meshing in the blade angle adjustment in the case of overspeed and causing the rotor blades to turn automatically out of the wind with the action of the wind forces. This safety system is independent of any auxiliary energy and therefore fulfills the requirement for the greatest possible availability.

Rotor blade

Already in the initial stage of the project, a fiber compound rotor blade was taken as a basis for GROWIAN. This was founded in the positive experience, on the whole, collected with the fiber compound materials in the area of primary structures and on the basis of expert opinion on the construction feasibility of large compound rotor blades. It was to be expected therefore that a sufficiently considered draft could be prepared within the period of the order.

Initiating construction and calculations, however, demonstrated that the 100 m rotor of fiber compound material projects into technologically unexplored territory to an extreme degree. The load on the rotor blades requires wall thicknesses, not yet controllable. The points conducting the force from the fiber compound structure into the steel construction

also represent sensitive problem points. Studies have produced results that at least an external portion of the blade can be manufactured with present knowledge of technology, but the further development must contain intensive research work on producing laminates and material strength. In addition to an extensive and statistically better founded static study of all planned materials at the expected operating temperatures, above all, dynamic tests with materials and parts will contribute to further clarification of the problems of a full-fiber compound rotor blade. A program in technology over several years for fiber compound rotor blades therefore appears practical and necessary.

With progressing preparation time in the project, the original full-fiber compound blade was first provided with a 12 m long steel section at the base of the blade due to the previously mentioned difficulties. /42 Subsequently, the middle section up to 30/32 m in the rotor blade divided into three lengths was designed as a steel shaft in the support structure. Finally, the remaining uncertainty in a rotor blade outer part in fiber reinforced structure also suggested drawing out the steel shaft virtually up to the blade tip and employing the fiber reinforced material for the external shaping of the rotor blade.

Work on the reinforced rotor blade

The rotor blade is positioned on the central steel portion with a rotor radius of 12 m and extends up to a radius of 50.2 m. For reasons of production and operation, it is divided into two halves, designated as middle section and external blade.

The known construction concepts of wing and rotor blade structures were examined as to applicability, also with respect to manufacturing the part in the near future.

From the variety of possibilities

- Two shafts, stringer-reinforced covering
- Several shafts, stringer-reinforced covering
- Several shafts with cross beams
- Several shafts with cross beams and sandwich covering in the rear profile section

a structure for with two shaft casings was selected. In the external blade, the double-shaft construction is terminated in a shell.

The separation points of the blade including the force conduction areas was a special problem point. The known force conduction by means of loops, adhesives, riveting had to be disregarded. The large wall thickness and blade depth, necessary in the present case although never before produced, required the resolution of the force conduction points by means of cascade connections at the shaft beams. The tolerance requirements led to a solution with tongue-fork connection.

The materials from which the reinforcement materials could be selected were

- GFK (glass fiber synthetics)
- CFK (carbon fiber synthetics)
- BFK (boron fiber synthetics)
- SFK (aramide fiber synthetics)

The first computations with GFK produced excessive wall thickness (90 mm) at inherent frequencies which were too low. BFK was rejected from the beginning due to the costs and production problems. SFK can only be applied to a limited degree due to the low pressure strength and also due to processing problems.

The level of experience with CFK provided the possibility of applying this material in the shaft beams and in the force conduction fingers. Sufficient rigidity and strength, in addition to the high material costs for carbon fiber led to the application of GFK in the torsion shell and cross beams. /43

The negative shell method of construction is employed as a basis for the production of the rotor blades, applying the manual laminating technique. Costs, storage capability, processing and exactness of hardening the building materials are in conflict with a rational production of large-scale rotor blades employing prepregs.

Autoclaves of this magnitude are not yet available for this purpose; a further division of the structure into smaller structural parts is not practical. The completed work clearly underlined the necessity for further development in order to apply fiber-reinforced materials in the construction of large-scale rotor blades.

The production and testing of a GROWIAN test shaft can be considered a first step in this direction, although employing conservative technology.

Rotor blade in reinforced steel construction

Alternatively to the rotor blade developed as a carbon fiber reinforced structure, a version with one steel shaft extending up to the radius of 30 m was studied and designed as supporting structure.

This rotor blade version consists in a steel casing shaft up to the area adjacent to the hub (Figure 23) around which an aerodynamic covering manufactured from glass fiber synthetics is placed. The external blade area is carried out in CFK structural form method as in the case of the reinforced rotor blade.

The rotor blade is divided into three sections for reasons of transport and handling. The separation points are situated at the blade radii $R = 15$ m and $R = 30$ m.

The steel shaft casing has a flat six-sided cross-section and is welded. It is arranged in the individual rotor blade profile between 5% and 40% of the depth. This arrangement had the effect that the center

of gravity of the shaft is situated in front of the $t/4$ line of the profile. The shape of the hexagon was selected in order to utilize the largest thickness of the profile in the individual cross-section.

In the blade root area, the hexagonal cross-section is converted to a truncated cone at values less than $R = 7.5$ m, ending with the bearing flange of the blade bearing. At the extreme end $R = 30$ m, the steel shaft is formed as a transverse force connection for the reinforcing structure. This is a tongue-fork connection, already proven in glider construction. This fulfills the task of converting the impact and pivotal bending moments into corresponding transverse forces. Figure 24 shows the function chart of the connection.

The aerodynamic profile fulfills the task of conducting the forces of the air into the shaft. This was divided into three main groups: blade nose, covering of the shaft beams, and profile end casing. For the range between $R = 15$ m and $R = 30$ m, the construction is presented in Figure 25. It is planned to manufacture the profile nose and profile end strip as form parts in the negative forms. The covering of the shaft beams is laminated manually, employing hard foam as support material between beam and laminate. The profile end casing consists in ribs in a sandwich construction, the GFK planks and the profile end strips. The assembly is carried out in stages: first the ribs are fastened at predetermined intervals on the steel shaft and bonded to the end strip. Subsequently, the planking plates are placed on the ribs, screwed down and bonded.

Waves and seams are ground filled with polyester daub and ground again in order to achieve the prescribed surface quality.

The external blade area is constructed as a CFK structure, as in the case of fiber reinforced rotor blades. This is a form structure with no ribs or additional stringers. For dimensioning the rotor blade in the steel shaft version, the computer program PROFI, developed by the DFVLR, Braunschweig for the fiber-reinforced rotor blade, was employed. The evaluation of the calculated stresses produced the result that in various areas the permissible stresses were exceeded. The resulting alterations in wall thickness are listed in the strength report for the steel shaft version.

Steel shaft rotor blade

Static and dynamic load tests carried out with CFK structural parts of the reinforced rotor blade have demonstrated that a number of improvements in the production method and in reproducing the quality of the material must still be achieved in order to fulfill the requirements for a long life span of these structural parts. This necessary further development must be carried out in a technology program.

Since an appropriate qualification of the CFK reinforced structure in the external blade area cannot be expected before the planned construction of the GROWIAN prototype, a prototype with a steel shaft extending up to the blade tip is proposed (Figure 26).

This rotor blade version has an untwisted, simple symmetrical, hexagonal steel case shaft as supporting structure. The steel case shaft is welded and converts to a truncated cone from the blade radius $R = 15$ m up to the connection at the hub. In the direction of blade depth, this is situated between 8% and 30% of the individual profile section.

The aerodynamic profile is manufactured from GFK reinforced material, as already described, and fixed at the shaft. The entire aerodynamic covering is produced in negative forms for the blade exterior area between $R = 30$ m and $R = 50$ m, caused by the required accuracy of profile contour and the surface quality.

For reasons of handling and transport, the rotor blade is divided into 3 sections, joined after production at the location.

Electrical Equipment

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Boundary system conditions

The designs for the electrical equipment of a large wind power plant pursue the aim of constructing a typical GROWIAN in the German North Sea coastal area connected to a medium-high-voltage system in the country.

The most important boundary conditions and requirements for system operations were defined as follows:

- Output of the GROWIAN will be fed into a 10 or a 20 kV system. In a 10 kV system, a short circuit power of approx. 100 MVA can be assumed, in a 20 kV system a short circuit power of approx. 150 MVA.
- The generator of the GROWIAN should be capable of supplying the idling power required by the consumers for effective power.
- The generator must be designed in such a way that a voltage band of $\pm 5\%$ of the system nominal voltage can be supplied at full effective and idling power.
- The varying capacity supply of the wind is to be smoothed to as great a degree as possible. Excess peaks due to gusts must not be permitted to "tip" the generator, i.e. a synchronous generator or a machine behaving like a synchronous generator may not achieve a state in which it can no longer be maintained in a synchronous function by the system.
- Synchronization is to be carried out in such a manner that practically no or only very slight effective and/or idling power peaks occur. Rough synchronization is not permissible. A possible voltage drop in synchronization should be less than 1.5%.

Selection and dimensions of the generator unit

An electrical machine with 3 MW nominal output and a nominal speed of 1,500 r.p.m. was employed as a basis for a typical GROWIAN. Solutions with constant and variable speed and with synchronous and asynchronous machines were studied for this machine. Costs, degree of effectivity, idling power requirements, dynamic behavior at the system, behavior in wind gusts, synchronization, reliability and ease of maintenance were employed as selection criteria in the preliminary study.

On the basis of these selection criteria, three variants remained from the preliminary selection for the final selection:

- synchronous machine with frequency converter in stator circuit,
- asynchronous machine with frequency converter in rotor circuit,
- synchronous machine with a fixed connection to the system.

Due to the considerable and not precisely predictable moment excesses in the application of a fixed speed synchronous machine and the effects on design (high overload capacity) and operations (possible tipping of the generator), the demand was made for a certain amount of speed variability, so that the fixed synchronous generator was no longer considered. /46

Of the two remaining variants, the asynchronous machine with frequency converter in rotor circuit was finally given the advantage. This is optimal with respect to the idling power requirements, easy to service with the very simple machine in the machinery housing with difficult access, and also favorable in price. The operation of the frequency converter remains within normal limits. A special advantage of the selected connection is the independent regulation possibility of effective and idling power. The frequency in the rotor circuit controlled by the frequency converter, virtually alterable without inertia, provides the machine with elasticity in wind gusts without producing special stress on the mechanical regulation of the wind turbine. Instead, the relatively complicated electrical equipment of a frequency converter in the rotor circuit of the asynchronous machine must be accepted (illustration in Figure 27).

By switching the rotor circuit from the frequency converter to a resistor, the machine remains in the system as an asynchronous machine in the case of large short-term wind speed increases and an accompanying speed increase to more than 115% of the nominal speed and can be resynchronized after a drop in speed.

For the dimensions of the generator unit, the following main data were employed:

nominal output	3 MW on the 6.3 kV busbar
nominal voltage in the stator circuit	6.3 kV
nominal frequency	50 Hz

nominal speed 1,500 min⁻¹
speed range ±15%
Enclosed cooling system with secondary cooling circuit by means of external air.

The selection of a machine with secondary cooling circuit was carried out because of the danger of salt deposits due to the cooling in ocean air, as must certainly be considered in the North Sea coastal area.

The design produced a machinery effectivity of 95.7% for full load. For the generator unit as a whole, i.e. with frequency converter and frequency converter transformer, the nominal effectivity is 94%. The weight of the generator amounts to approx. 12 t.

Components of the main circuit and auxiliary service

For transmission of the electrical output via the swivel joints, cable rotary equipment or sliprings were considered in principle. Because of the lack of space and the larger freedom in wind direction guidance of the machinery housing, the slipring transmission was given the advantage. For the power cable from the stator and rotor circuit and for the three-phase current auxiliary service, a ventilated cable channel is planned in the tower.

Since GROWIAN was developed as a standardized typical plant, but the medium-high-voltage systems in the country in Germany have various voltages, a basic transformer feed between the individual available medium-high-voltage and the voltage of 6.3 kV advantageous for the machine was planned. /47

In the switch house at the base of the tower are the 20 or 10 kV, the 6.3 kV and the 380 V auxiliary service switching equipment, the frequency converter and the field resistance as well as various service boards, while the three transformers (main transformer, generator transformer, auxiliary transformer) are in the open.

For reasons of standardization, it was assumed that the auxiliary requirements of a GROWIAN is taken from the 6.3 kV busbar. Wherever the location of the plant permits, a low voltage feed should be provided, independent of the medium-high-voltage line on which GROWIAN is connected. Since this often cannot be realized, and emergency current aggregates and a battery-fed inverter are planned for the emergency current supply.

6. Construction and Assembly

The construction and assembly of the wind energy plant is carried out with extensively prefabricated structural parts with the exception of earth and cement work.

The transport to the building site, wherever possible on a waterway, causes no difficulty in the steel tower parts or sections of the machinery housing, or in the partial pieces of the rotor blades and the hub.

The core idea of the GROWIAN assembly concept is the moveability of the machinery housing along the tower with the tower shaft penetrating the machinery housing. The lifting motion is generated by a lifting tackle arrangement at the top of the tower and in the machinery housing collar.

The advantage of this procedure is in the simple assembly possibility of the entire machinery housing including the rotor on the ground and in dispensing with an expensive large mobile crane, required for the construction height and the masses to be moved. Moreover, the tower head cannot be raised completely with available hoist equipment. The alternative possibility of assembly for approx. 25 t heavy individual parts at a height of 100 m presents unforeseeable technical problems, resulting among other things from the alternating wind loads. The chosen solution will probably be especially useful in the first years of operation, since it may be expected that extraordinary inspections and work in testing operations will occur, requiring that the tower head be lowered. The assembly possibility, however, makes it necessary to adjust the machinery housing structure to the required free space for the tower passage. Figure 28 shows the course of assembly.

Construction of the tower

The concept of assembly provides construction of the steel tower planned for the initial plant of 9 m long sections including insulations with the aid of a mobile crane or a climbing crane with simultaneous step-by-step welding. The connection to the tower foundation is produced by short tensile anchors. The tower building fulfills the demands placed on high-rise buildings in every stage of construction.

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This even applies when the tower guidelines are missing.

The cement tower is constructed with sliding forms. The interior is finished as construction proceeds. The operations building is constructed at the same pace as the tower construction.

No binding statements can be made on the foundation of the tower building before precise knowledge is available on the ground condition.

Assembly of the machinery housing

At a tower height of 10 to 15 m, the guideline ring and the form parts of the machinery housing are placed over the tower shaft. The connections of middle and rear portion as well as to the hub tubular support are carried out with welded seams. By supporting the machinery housing on an assembly subconstruction, the collar and azimuth support ring with bearings can be mounted.

Finishing the interior with walkways and support construction for transmission, generator, hydraulic crane and further equipment is subsequently carried out.

Rotor assembly

The rotor assembly begins at the machinery housing still positioned

on the ground by inserting the rotor shaft into the corresponding bearings and mounting the pendulum frame. The rotor blades are constructed in a horizontal position and inserted into the support points in the pendulum frame. The three sections, in which a blade is invited, had already been provided with sections of glass fiber-reinforced synthetic materials at the factory, excluding only one work area at the point of connection. The shaft connection is carried out by screws and welding. The profiles of the connection points is correspondingly supplemented. The completely mounted rotor is first balanced on the ground and is required at the tower.

Raising the tower head

After completion of the tower and machinery housing with the rotor, raising the tower head is carried out with the tower shaft penetrating the machinery housing.

The lifting motion is generated by six winches set around the entire tower with hoisting cables passing at the tower base over fixed pulleys into the interior of the tower. The lifting equipment, consisting in three pairs of lifting tackle arranged at the circumference of the tower with fixed pulleys at the top of the tower, raises the tower head.

Since the center of gravity of the tower head is outside of the tower axis in the direction of the rotor, a pulling force must be exerted /49 at the spur of the machinery housing during the lifting process and until the tower guidelines are in place, shifting the center of gravity to the tower axis. The pulling force is reduced by a mass (approx. 20 t), held on a cable above the ground.

During the lifting procedure, the wind speed may not exceed 10 m/sec.

The guideline ring with cables is also raised since it is fixed at the machinery housing collar. After anchoring the ring, the cables are prestressed at the stay foundations.

7. Operations

With the progressive development of machines, in addition to hardware the software has gained in significance. Therefore the application of a complicated technical device, in this case represented by the projected wind energy plant, requires well-adjusted procedures in operation. These procedures are designated as operations; they determine in what manner and with what aim GROWIAN is to be operated.

The operations set down at the present time are based partially on hypothetical assumptions, which can only be tested and, wherever necessary, corrected in test operation of the wind turbine.

Operational procedures

In operating GROWIAN, function sequences are controlled by the operations logic. Systems carry out the individual functions, monitor the manner in which they are carried out and report the operating

parameters to the operations logic.

The operations logic determines from the entirety of the operating parameters and from the environmental conditions present at the time

- the plant condition
- the operating phase at the time (e.g. running up)
- the function to be controlled (e.g. guiding into wind direction)
- the appropriate required and limit values (e.g. required speed)

When limit values are exceeded, or as the consequence of a direct order, e.g. on the control position, the operations logic switches to the appropriate new plant condition with corresponding required and limit values to be maintained by control of the appropriate functions.

Operating ranges

According to the prevailing wind speed, three operating ranges are differentiated:

- | | | |
|------------------------|--------------------------------|------------|
| - partial load range 1 | at wind speed of 5.5-9.3 m/sec | <u>/50</u> |
| - partial load range 2 | at wind speed of 9.3-12 m/sec | |
| - full load range | at wind speed of 12-24 m/sec | |

In the partial load ranges, the output of the turbines is less than 3 MW, in the full load range the nominal output of 3 MW is constantly generated. The wind speeds are based on a 10 minute average, measured at the height of the hub.

Operating cycle

A normal operating cycle comprises running of the plant, operations with output into the system and the regulated stoppage with subsequent standstill (Figure 29).

The designated wind speeds have the following significance:

- V_{S1} : Start speed (6.3 m/sec) from standstill or waiting position. The arrow pointing above signifies running up. When the lower speed limit of $0.85 \times n_N$ is reached, the generator can provide output. The speed is maintained in the variation range by the regulating system.
- V_N : Nominal wind speed 12 m/sec. At values below this, the plant produces a nominal output less than 3 MW. Above 12 m/sec the full output of a constant 3 MW is available at nominal speed.
- V_{H1} : Halting wind speed. Wind at 24 m/sec limits the working range of the plant. In the case of prevailing wind above 24 m/sec, the plant is stopped or driven in waiting position.
- V_{H2} : At any wind speed between V_{H1} and V_{H3} the plant may be stopped (e.g. no current required).

V_{H3} : Wind speeds less than 5.5 m/sec are not sufficient to maintain GROWIAN at idling speed in the operating speed range. The waiting position is maintained at lower speed.

V_{H4} : When the wind velocity is reduced below V_{H4} (4 m/sec) the speed of waiting position cannot be maintained. V_{H4} The rotor is stopped.

V_{S2} : After stopping due to excessive wind speed (V_{H1}), the plant can be run up again at a wind speed greater than V_{S1} and smaller than V_{S2} , maximum 22 m/sec.

Exceeding the maximum operating wind speed for a short period does not lead to immediate stopping, since the plant should be operating up to an average speed of 24 m/sec.

Normal operations

Dependent upon the circumstances of the environment, the course of normal operations is controlled in "operation phases", specifically:

- running up
- load operation
- stopping
- waiting position
- standstill

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GROWIAN is switched on from the control position by the user or from the control position of the plant. Switch on from the control position of the plant requires the release by the user ("command of the user").

With the switch-on signal, all consumers of auxiliary service receive fundamental switch release.

By means of the operations logic, the systems belonging to the initiation of operations are switched on and the available measured values and signals are called for and processed.

Running up

In the process of running up, the rotor is accelerated without load from standstill up to nominal speed.

GROWIAN can be run up, when it applies that:

- demand of user is present
- high-voltage system is ready to receive
- wind speed between 6.3 and 22 m/sec in a ten minute average value and momentary value greater than 6.3 m/sec
- all systems ready for operation
- rotor on the lee side

Fulfilling these running up conditions is automatically checked in a check out procedure by the operations logic. The measured values for the wind speed and wind direction at the time are supplied by the measuring station at the windward spur of the machinery housing.

Running up process is initiated by adjusting the blade adjustment angle to the defined running up position.

The rotor brake is closed and holds the running up momentum of the forces in the air. The running procedure begins with releasing the rotor brake. Under the effect of the momentum of the force in the air, the centrifugal mass of the rotor is accelerated, the rotor gain in speed. The blade adjustment angle in the direction of operating position is adjusted.

The adjustment speed is regulated during the running up procedure in such a manner that even at running up wind speed a rotor speed gradient is present, sufficient for passing the critical tower inherent frequency.

When nine-tenths of the nominal speed is achieved, the generator is connected and synchronized with zero output. The generator is loaded and supplies output into the system.

Load operations

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According to wind speed, the plant is in the partial load ranges or in the full load range.

The wind direction guidance is active in load operations and constantly ready for application. It guides the rotor with the wind, when the wind direction deviation, added in time, reaches a threshold value. In the meantime, the tower head is solidly braked.

The transition between the individual operating ranges is carried out continuously. Differing operational methods of output regulation is presented in the section of this report on that subject.

Stopping

Stopping is carried out in normal operations when

- the user calls for this (e.g. inspection, etc.),
- the wind is not sufficient for maintaining the waiting position

With the command "stopping", the operations logic provides the rotor with constantly sinking speed required values down to the zero value.

The blade adjustment angle is altered in such a way that a constant reduction in speed occurs. Through the controlled application of the rotor brake, standstill is achieved with blades steering 15° from the vertical. The blade adjustment angle is maintained in standstill-flag position.

Waiting position

An operating state is designated as "waiting position" in which the rotor circulates at a speed below the normal operating range and external to the resonance range and provides no output. The speed is

set at 9 r.p.m. $\pm 25\%$. Speed regulation is carried out solely by adjusting the rotor blades. The waiting position applies at wind speeds below 6.3 (5.5) and above 24 m/sec. All systems are ready for operation or in operation and are controlled by the operations logic.

The waiting position offers the following advantages compared to the stationary rotor:

- the load is less than stochastic loads at standstill,
- rapid achievement of the load operation with output production,
- controlled guidance of the plant.

Since GROWIAN produces no output in the waiting position, operation in the waiting position is then especially practical, when assuming load operation within the foreseeable future is expected or a standstill would lead to a possible danger for the plant (high wind speed, storm fronts).

Standstill

In standstill, GROWIAN is maintained ready for running up until the command for switch-off or running up is received.

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The supply system functions normally at a standstill. The rotor is solidly braked with blades in a flag position 15° to the vertical position of the blades. The logic behind this position is, on the one hand, to prevent snow masses on the rotor blades and, on the other hand, to keep the machinery housing and the hub out of the range of pieces of ice possible falling from the upper blade.

The wind direction guidance is carried out solely by the forces in the air exerted on the rotor and is protected by the overspeed safety device operated on centrifugal force in the tower head rotary drive.

When the plant is not ready for operation, it is in the operating position "switch-off".

Maintenance

In addition to the customary maintenance for technical devices, GROWIAN will require special inspection and maintenance, especially at the rotor blades. These serve for checking the blade surface in two aspects. First, the aerodynamic surface quality is of interest, also included in the output. The roughness can be greatly increased due to atmospheric pollution and dead insects; to what degree rain provides a cleansing effect must still be clarified. In addition, it is necessary to examine the blade surface for cracks, impacts or hail grains, etc. or the long-term strength of the GFK surface.

The accessibility to the rotor blade is made possible by 2 construction characteristics of the plant. The rotor can be inclined towards the lower end at vertical position of the blades to such an extent that the lower rotor blade can be stopped in direct proximity to the tower shaft.

Furthermore, the tower is surrounded by a maintenance platform, moveable along the length of the tower, extending to the blade for inspection with the aid of suitable extension platforms. Work gondola at two hydraulic extensions expand the working range still further (Figure 30). The available maintenance equipment can also serve for repairs and renovation of the surface protection in power and blades.

Maintenance and repairs in the machinery housing and in the area of the hub may also be combined with the transport of loads (adjustment spindles, motors, etc.). These tasks are carried out by a hydraulic crane installed in the machinery housing.

Work can only be carried out in the hub area with stationary rotors. The access is possible through openings in the steel construction.

8. Safety Concepts

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The advance of wind energy utilization into the area of plant output of several MW and the lack of applicable safety regulations for such plants require a safety concept which must satisfy two opposing demands. On the one hand, maximum safety is to be aimed for, on the other hand, the feasibility of the plant should not be placed in question from the beginning by excessive dimensions and overloading with redundant systems.

Since in a prototype plant, however, somewhat greater expenditure for safety precautions is justified to compensate for the deficit in experience, this problem sphere was paid special attention. Several of the measures appearing necessary at the moment may become dispensable in a later development stage of wind energy utilization.

Dangers for operating safety or even the existence of the wind energy plant may stem from external and internal circumstances. Among the external sources of danger are:

- weather conditions (wind, lightening, ice coating, etc.)
- foreign influence (aircraft impact, vandalism, earthquake, etc.)

Internal danger sources are found in:

- malfunctions of aggregates
- resonance phenomena in structural parts
- uncontrolled kinetics in plant components.

As a consequence of irregularities, an overload with material failure may occur, perhaps leading to function failure or to partial or total destruction of the plant.

With the exception of the case of foreign influence due to aircraft crash, earthquake and similar cases, however, the risks listed can be controlled by appropriate design and construction and suitable selection of safety equipment.

At another point in the final report, the load cases for GROWIAN are described. The definition is of decisive significance for the safety of

the plant, since the wind loads naturally place the greatest stress on the structural parts. It must be ensured that the maximum load occurring once within the life span will be assumed without violent fracture, even if this case does not occur until the end of the computed life span when a collection of partial damage from previous stresses has already occurred. A further point is the correct application of the load change numbers for the operating loads below the maximum load in order to exclude fatigue fractures.

A continuous control with respect to material fatigue phenomena, especially at the rotor blades, is considered necessary at least in test operation of the wind turbine.

Sufficient grounding serves as protection against lightening. In case of icing of the rotor blades, the plant is or remains stopped. /55

The malfunction of aggregates cannot practically be excluded. The consequence of damage, however, is prevented by redundant systems, suitable automatic control and/or locking systems. These and similar procedures are present knowledge in technology.

Vibration phenomena must be considered especially critical in large wind energy plants. This applies both to the aero-elastic behavior of the rotor blades and the occurring vibration interference between rotor and power. According to calculations on the total dynamics, taking into consideration complicated interweaving of individual processes, the inherent frequencies are placed at a sufficient distance from the source of excitation as a precautionary measure. In addition, the possibility is not excluded to introduce corrections of a vibration technical nature by the subsequent installation of masses in the tower and machinery housing, by alteration of the spring constant at the tower head connection of the prestress force at the tower guidelines.

Consideration of cases of disruption is incomplete when it does not include the occurrence of uncontrolled processes in the plant. For GROWIAN, the event of great consequence may be seen in the uncontrolled power intake of the rotor. This case may occur when the blade adjustment equipment fails. Since only short-term overloads are accepted by the generator, the excess power would then convert to speed increase. The maximum speed is set at 1.3 times the nominal speed, limited at 1.5 times the value for short-term overswinging.

Independent of the regulation and control equipment, a special safety system therefore acts in the case of excess speed, designated as emergency switch-off or blade angle release. This has the effect that the blade adjustment angle is reduced solely under the influence of the aerodynamic forces in the direction of a state with no load, the so-called flag position. Therefore, not only is a further assumption of power prevented, but the rotor is also braked to a rotary motion with no danger.

A mechanical rotor brake, acting at the main transmission exit, provides an additional contribution for securing the speed.

9. Influence on the Environment

Wind energy plants have a neutral function with respect to the environment. There are no material emissions. The motion of the rotor blades through the air generates noises, comparable to those of gliders. At a distance of two to three rotor diameters, noise is no longer perceived according to experience up to now with smaller wind turbines. Any effect on the flight of birds has not yet become known.

The energy drawn from the wind causes a reduction in wind velocity. /56
With respect to the immense air space, however, this effect does not signify any interference in nature or weather. Since wind power plants are constructed in areas especially exposed to wind, a certain wind protection function (similar to trees and hedges) can even be attributed to them.

Even under the assumption of parts falling from the plant, property and personal damage may be excluded, since the aerodynamic requirements on the flow of air in front of the wind turbines exclude a location in settled areas. Whenever necessary, sufficient safety zones are defined.

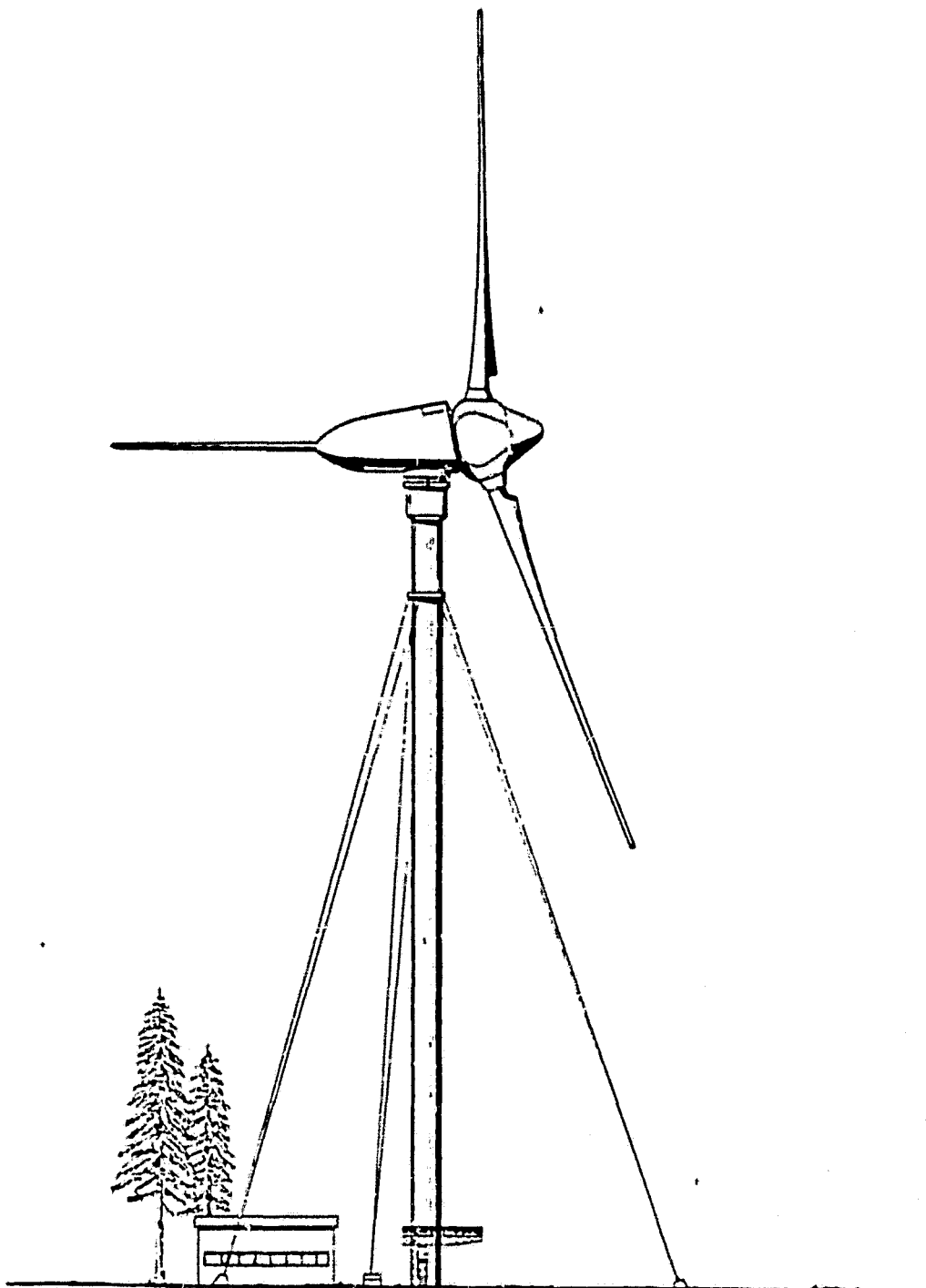
The optical effect of large windmills in the landscape remains. The slim shape of the tower dependent on financial and technical reasons is unnoticeable in comparison to large steel lattice towers and triple leg constructions. The machinery housing at the top of the tower has a shape similar to an aircraft fuselage. It will be possible to present wind energy plants both in a form suitable to the technical function and satisfactory in the relationship to the surroundings by suitable color design.

List of Figures:

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- Figure 7: Connection between rotor performance, speed and wind speed for GROWIAN (medium rough profile)
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- Figure 28: Power and machinery housing assembly
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a. Große Windenergieanlage
GROWIAN 3MW

Key: a, large wind energy plant

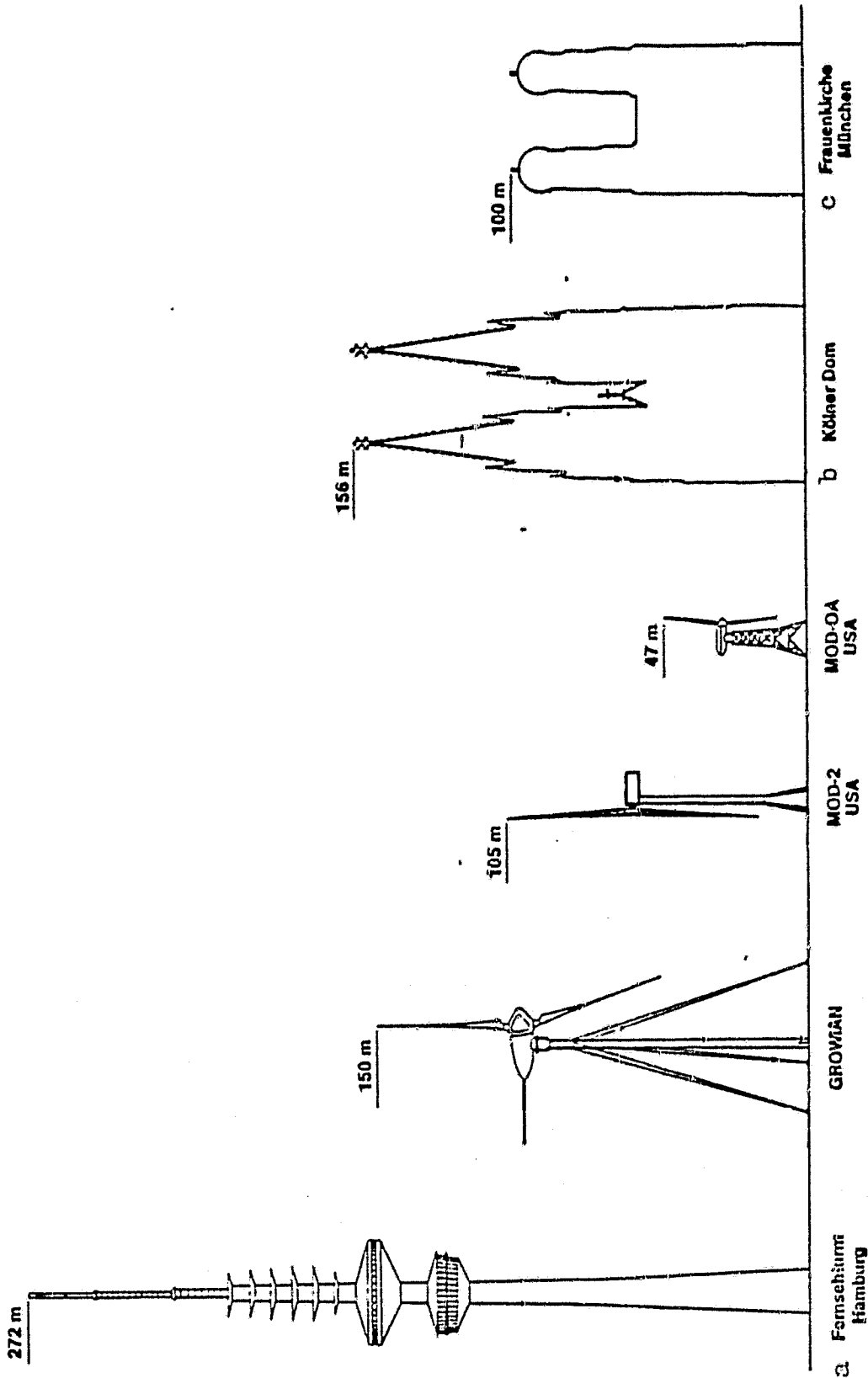


Figure 1: Comparison of Size

Key: a. Television tower in Hamburg
b. Cathedral in Cologne
c. Church of Our Lady in Munich

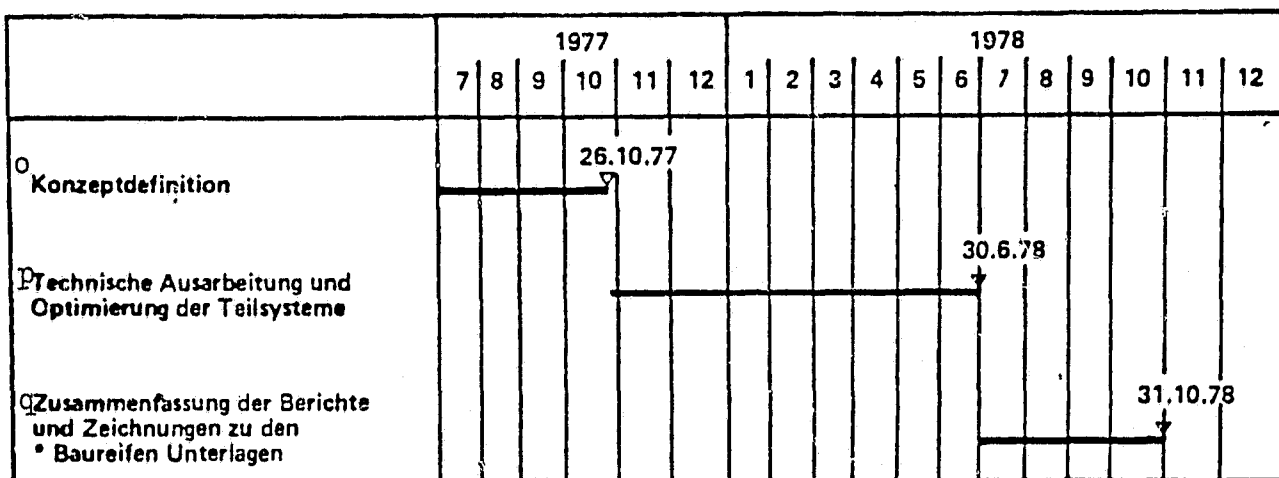
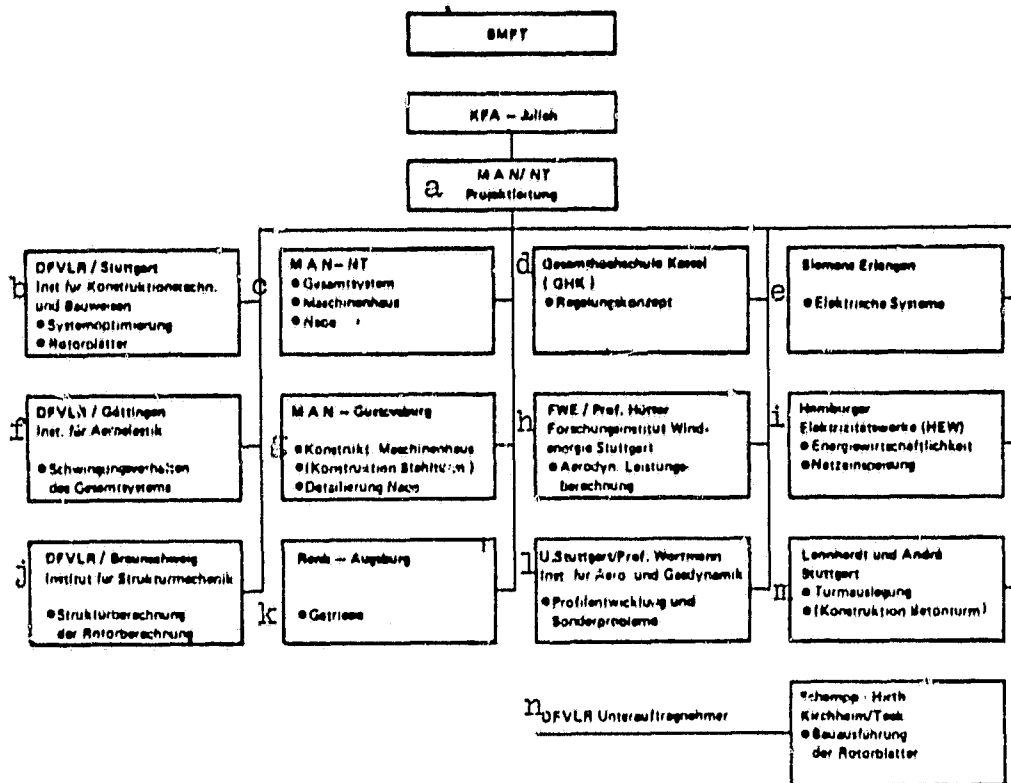


Figure 2: Project Organisation and Schedule

(See Following page for key)

- Key to Fig. 2:
- a. Project Management
 - b. Institute for Construction Technology and Building
 - System Optimization
 - Rotor Blades
 - c. - Entire System
 - Machinery Housing
 - Hub
 - d. University in Kassel
 - Concept for Regulation System
 - e. - Electrical Systems
 - f. Institute for Aeroelasticity
 - Vibration Behavior of Entire System
 - g. - Construction of Machinery Housing
 - (Construction of Steel Tower)
 - Details for Hub
 - h. Research Institute for Wind Energy in Stuttgart
 - Calculations of Aerodynamic Performance
 - i. Electric Utility (E.ON)
 - Energy Profitability
 - Systems Feed
 - j. Institute for Structural Mechanics
 - Structural Computations
 - Rotor Computations
 - k. - Transmission
 - l. University of Stuttgart - Institute for Aerodynamics and Gas Dynamics
 - Development of Profile Sections
 - Special Problems
 - m. - Tower Design
 - (Construction of Cement Tower)
 - n. DFVLR Subcontractors
 - Construction of Rotors
 - o. Definition of Concepts
 - p. Preparation and Optimization of Partial Systems Technology
 - q. Combining the Reports and Drawings in the Documents for Complete Construction

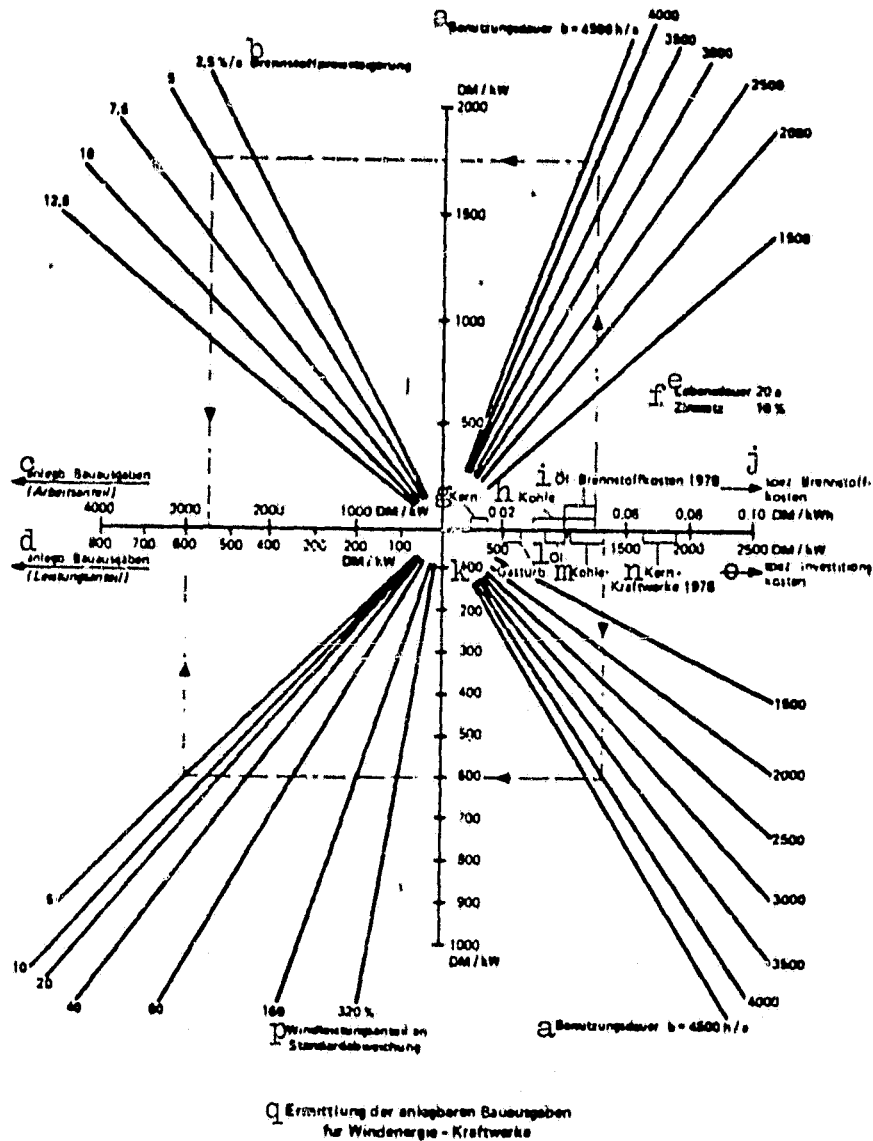


Figure 3: Diagram on Profitability Calculations

- | | |
|--|--------------------------------|
| Key: a. Duration of use | g. Nuclear costs |
| b. Fuel price increase | h. Coal costs |
| c. Invested construction costs (work portion) | i. Oil fuel costs |
| d. Invested construction costs (performance portion) | j. Special fuel costs |
| e. Life span - 20 years | k. Gas turbine power plants |
| f. Interest 10 % | l. Oil power plants |
| | m. Coal power plants |
| | n. Nuclear power plants - 1978 |

(Key continued on following page)

Key for Figure 3 continued:

- o. Special investment costs
- p. Wind capacity portion of standard deviation
- q. Determination of invested construction costs for
wind energy power plants.

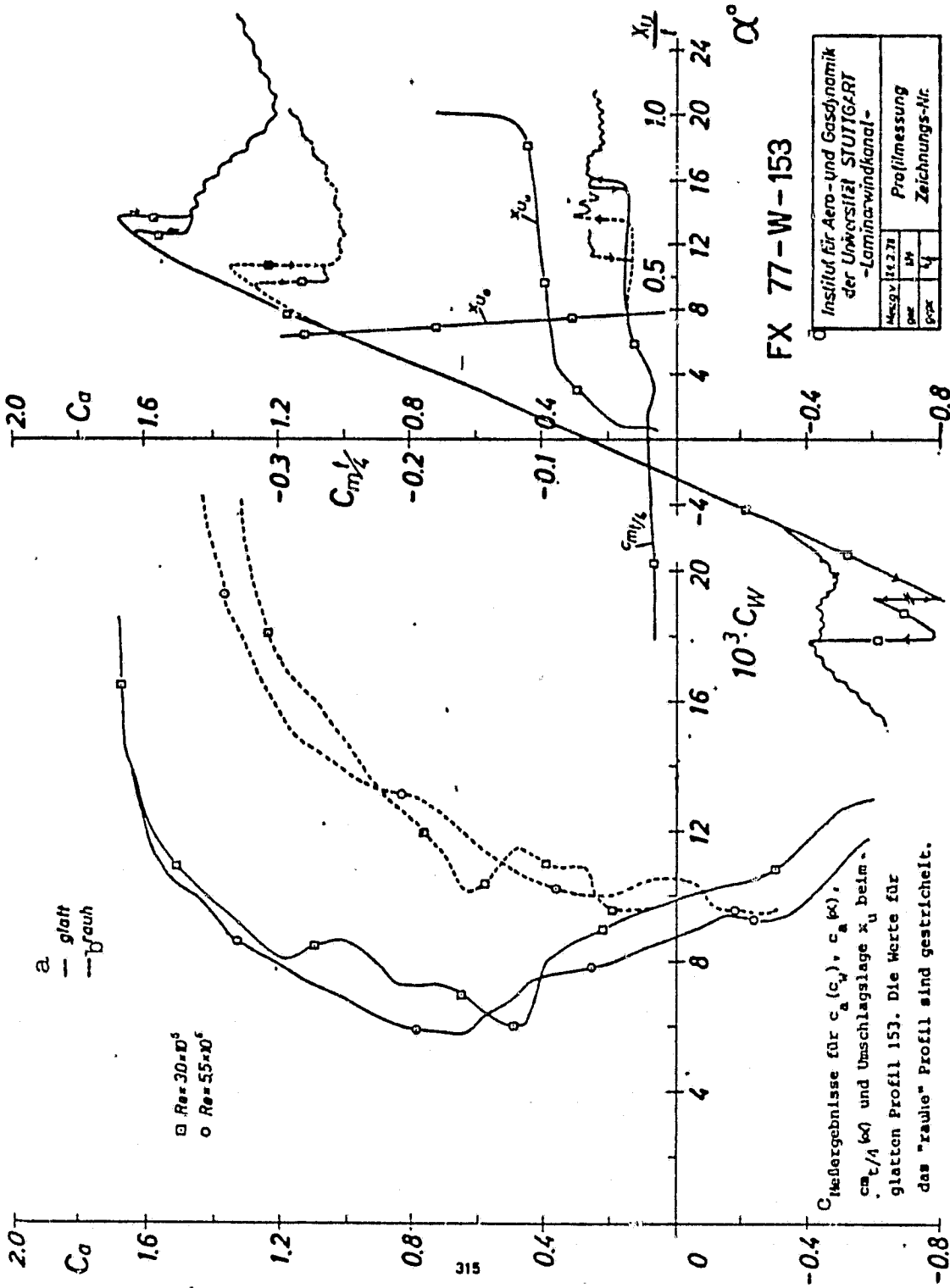


Figure 4: Lift and Drag Coefficients

Key: a. smooth c. Measurement results for $c_a(c_w)$, $c_a(\alpha)$, $c_{m1/4}(\alpha)$ and transition position x_u with smooth profile 153. Dotted lines denote rough profile.
 b. rough
 d. Institute for Aerodynamics and Gas Dynamics of Stuttgart University - Laminar Wind Tunnel. - Profile Measurement - Drawing no.

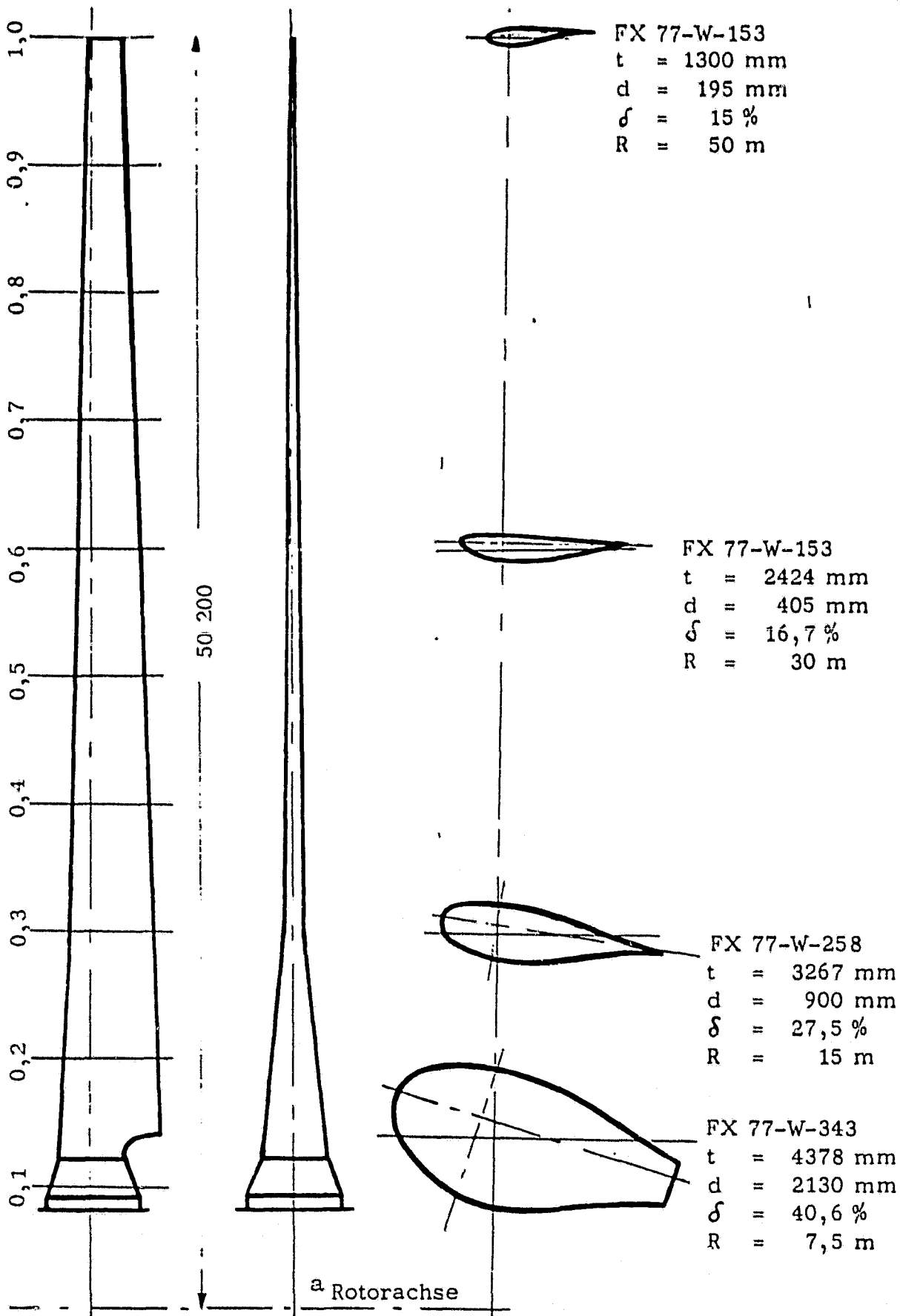


Figure 5: Rotor Blade with Profile Sections

Key: a. Rotor axis

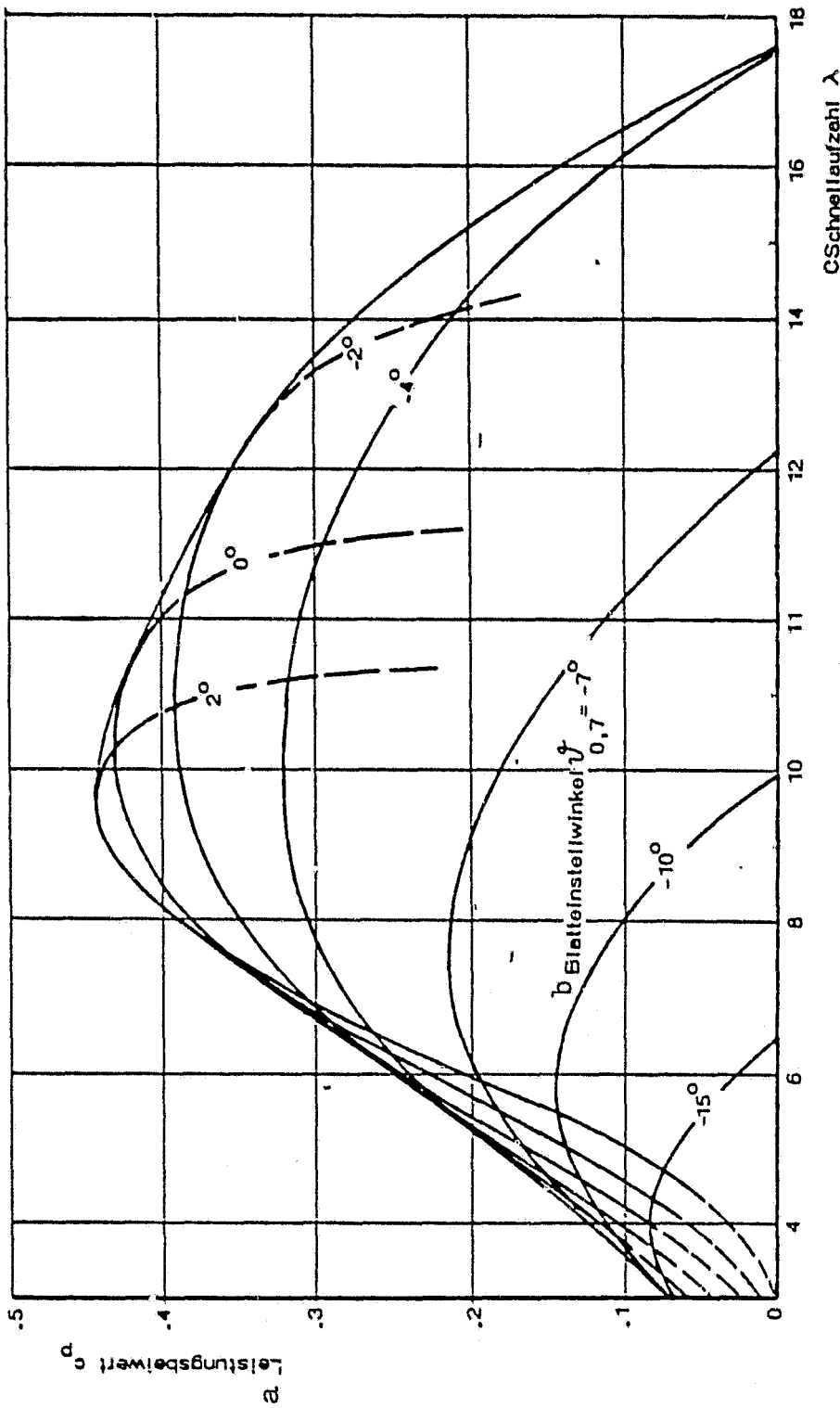


Figure 6: Rotor Performance - Envelop of Characteristic Curves for GROWIAN (medium rough profile)

Key:

- a. coefficient of performance
- b. blade adjustment angle
- c. rapid drive number

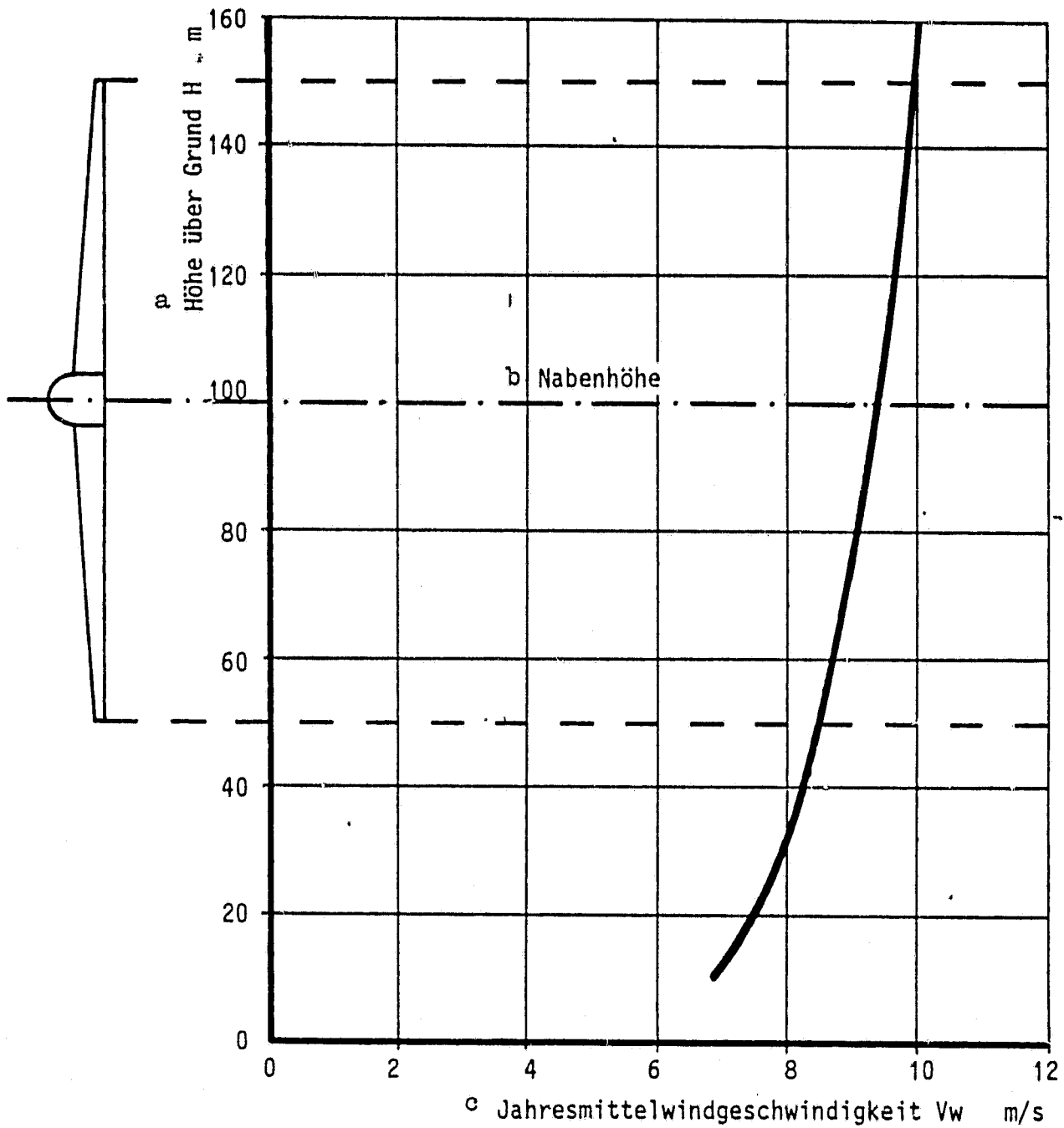


Figure 8: Height Profile of Annual Average Wind Speed for List on Sylt

Key: a. Height. above the ground
b. Height of Hub
c. Annual average wind speed

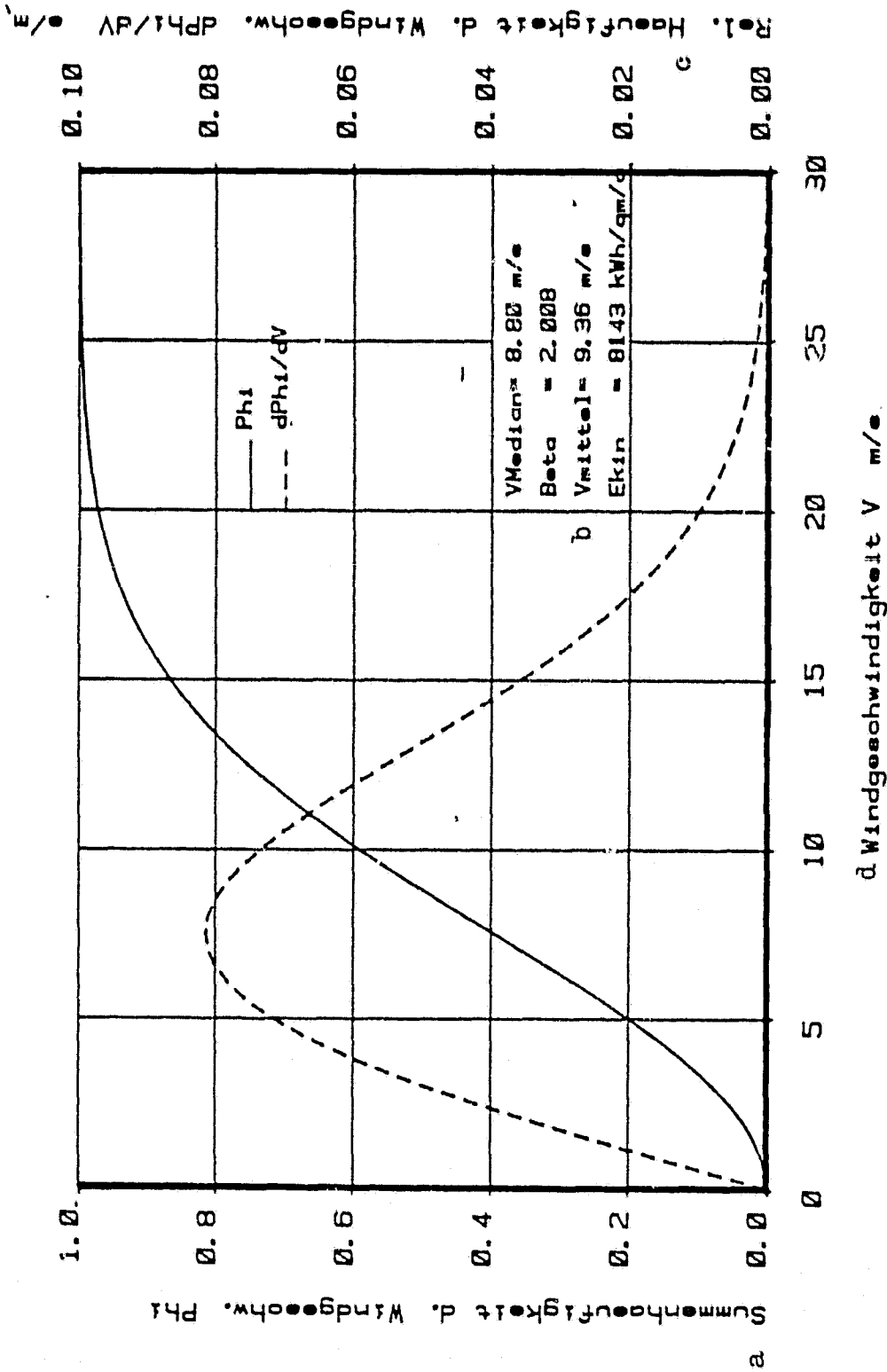


Figure 9: Wind Speed Distribution for List (Sylt)

- Key:
- a. Summated frequency of wind speed Φ
 - b. V-average
 - c. Relative frequency of wind speed
 - d. Wind speed

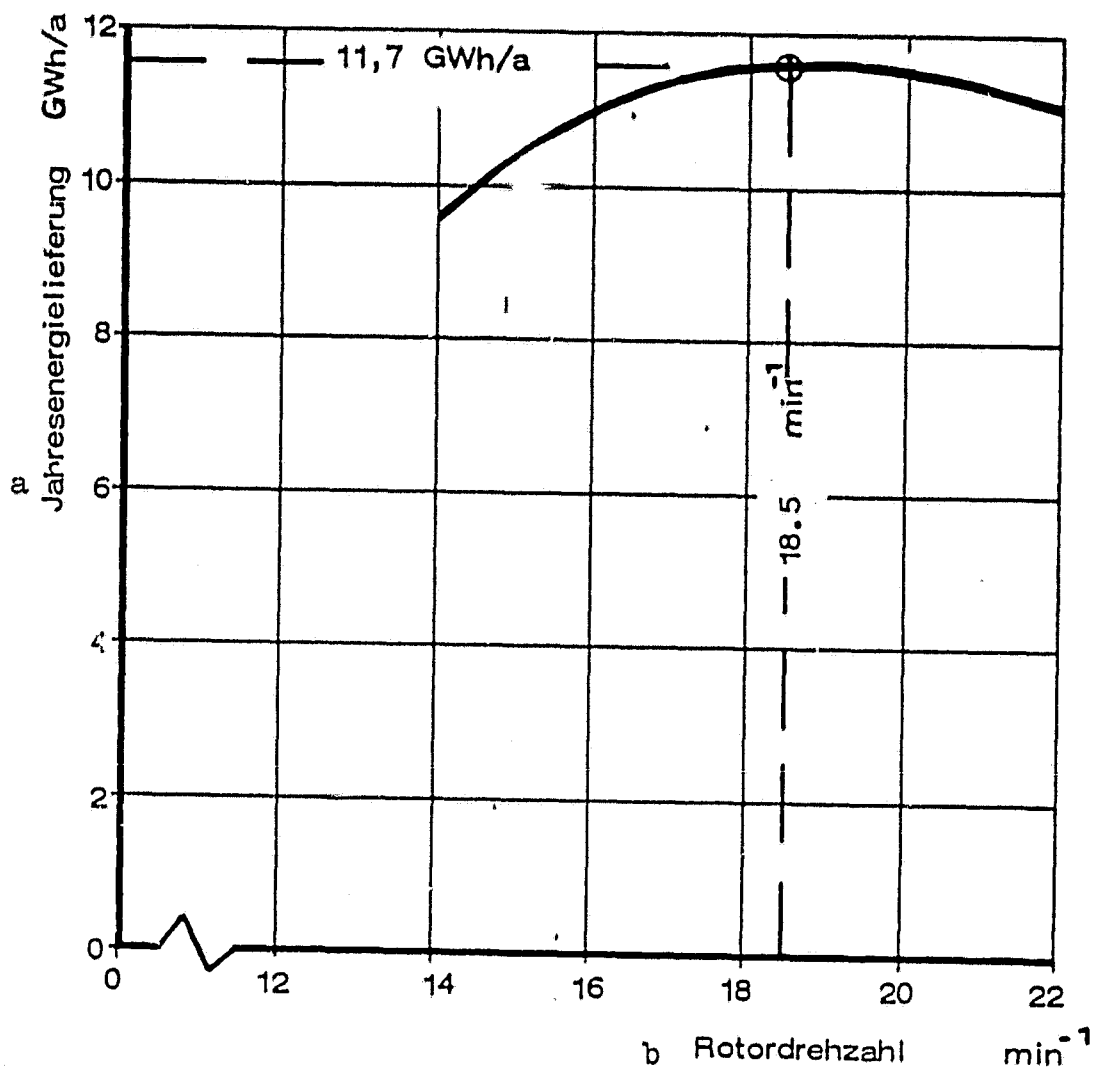


Figure 10: Annual Energy Production as a Function of Rotor Speed for GROWIAN with Wind data from List (Sylt)

The deviation in comparison to the annual energy of 12 GWh/annum indicated elsewhere results from the presently not yet founded assumptions on duration of wind speed and height distribution.

Key: a. Annual energy production
b. Rotor speed

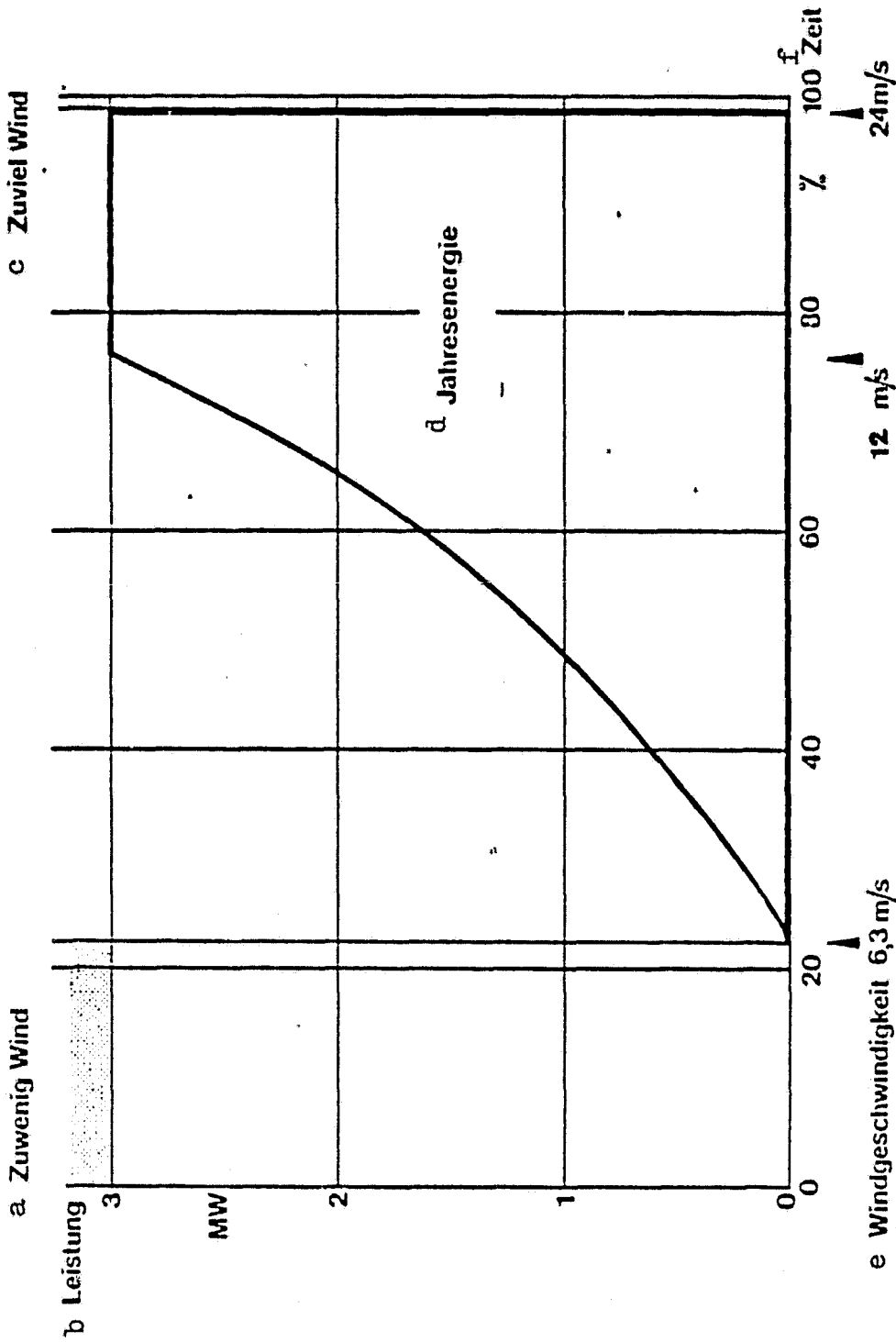


Figure 11: Curve of Constant Performance

- Key:
- a. Wind speed too low
 - b. Performance
 - c. Wind speed too high
 - d. annual energy
 - e. Wind speed
 - f. Time

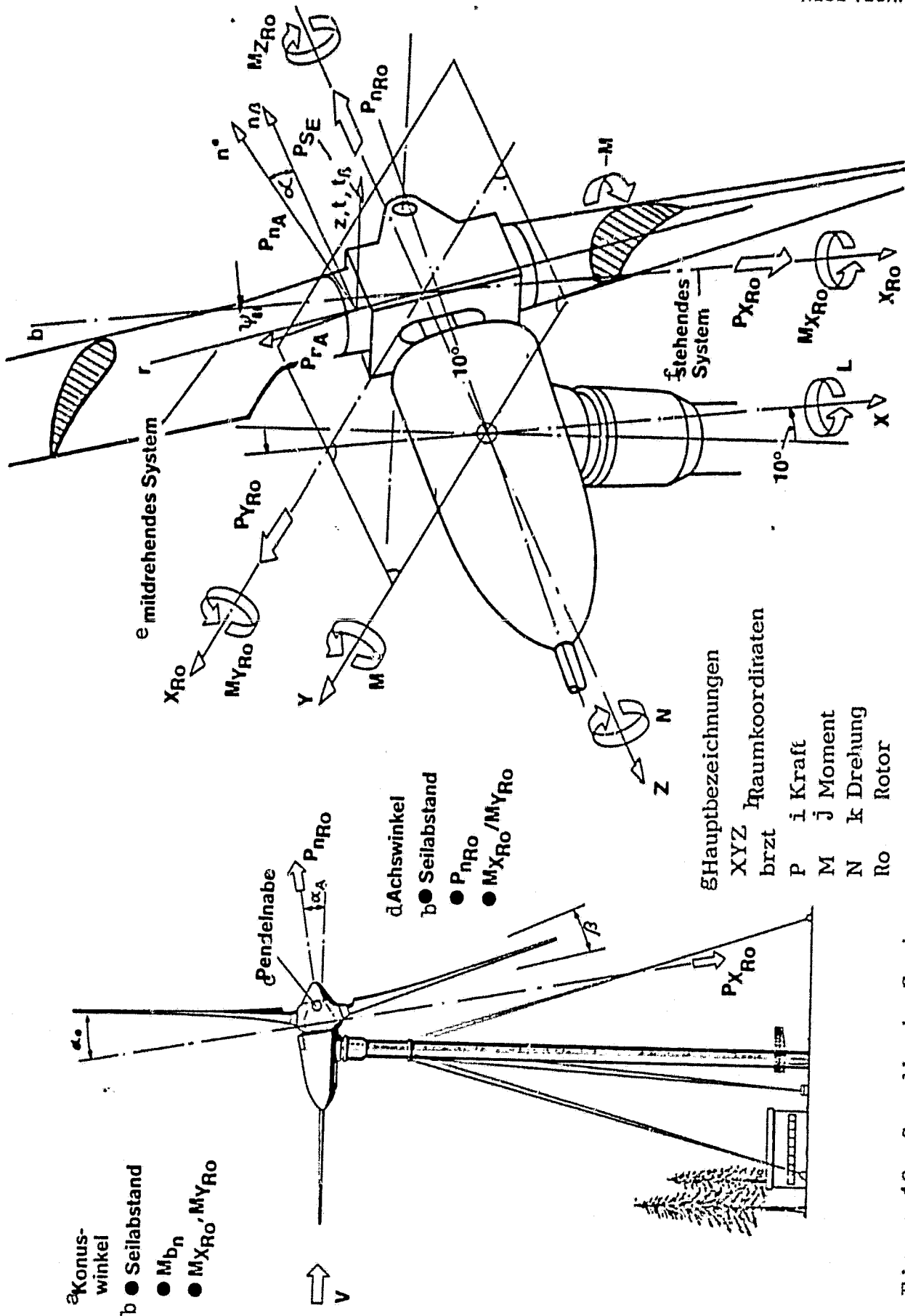
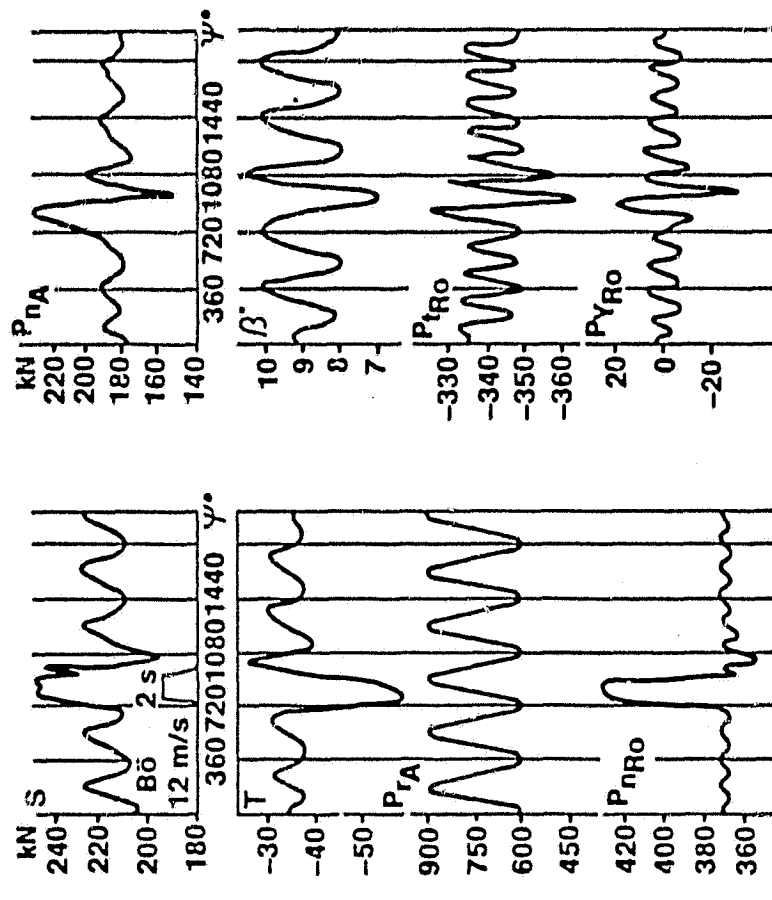
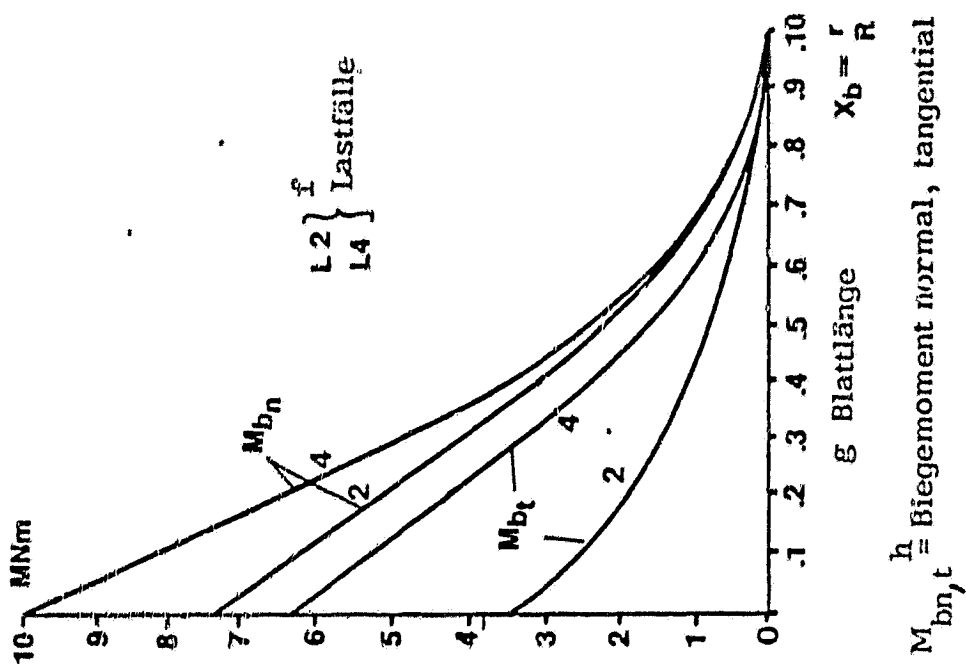


Figure 12: Coordinate Systems



- a S Schubkraft
b T Tangentialkraft
c P Rotorkräfte nach Bild 12
d β Pendelwinkel
e Rotordrehwinkel

Figure 13: Forces and Moments at the Blade

- Key: a. thrust
b. tangential force
c. rotor forces according to Fig. 12
d. Pendulum angle
e. rotor angle of rotation
f. load cases
g. length of blade
h. bending moment normal, tangential

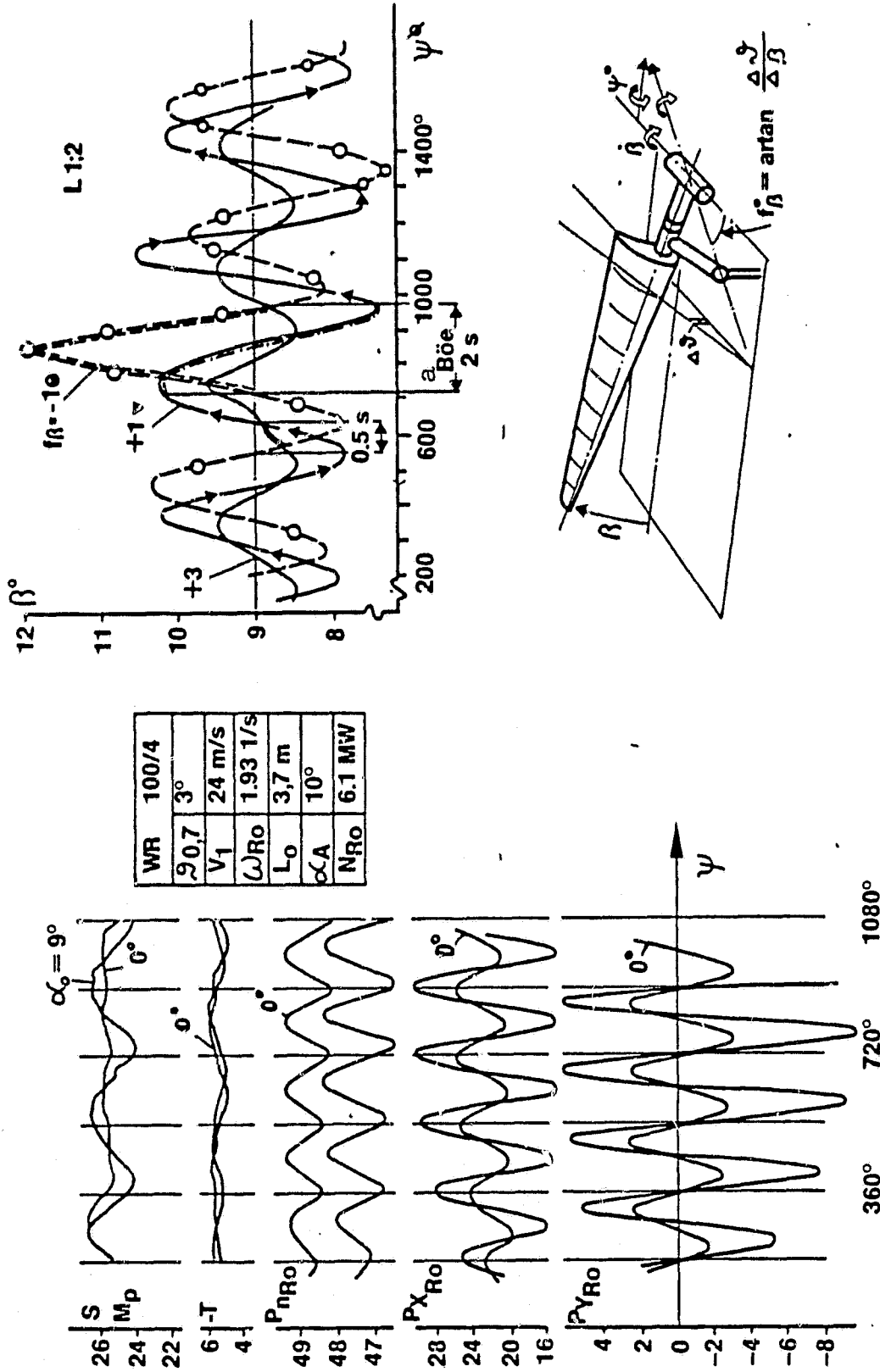


Figure 14: Load average values and amplitudes

Key: a. gust

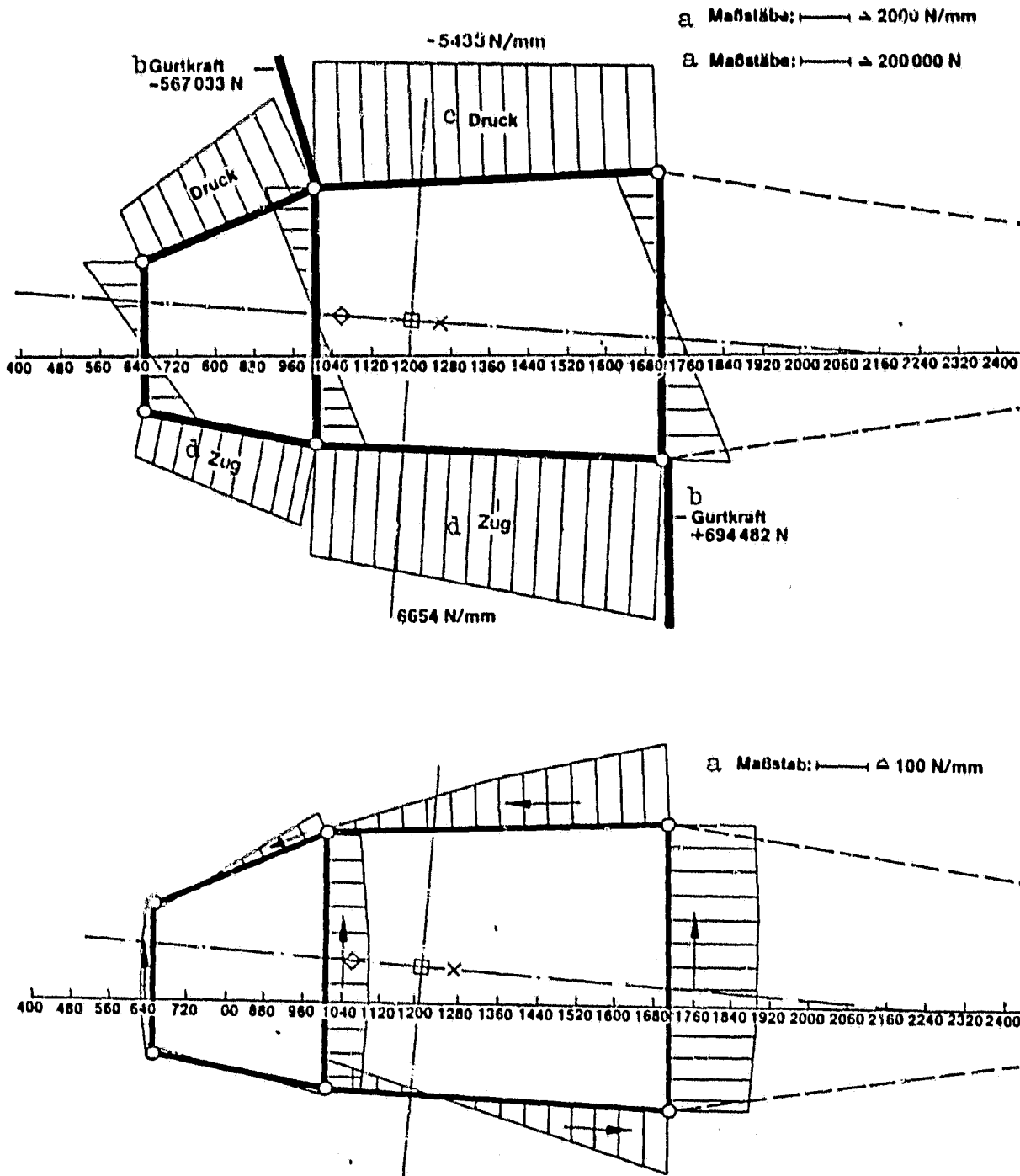


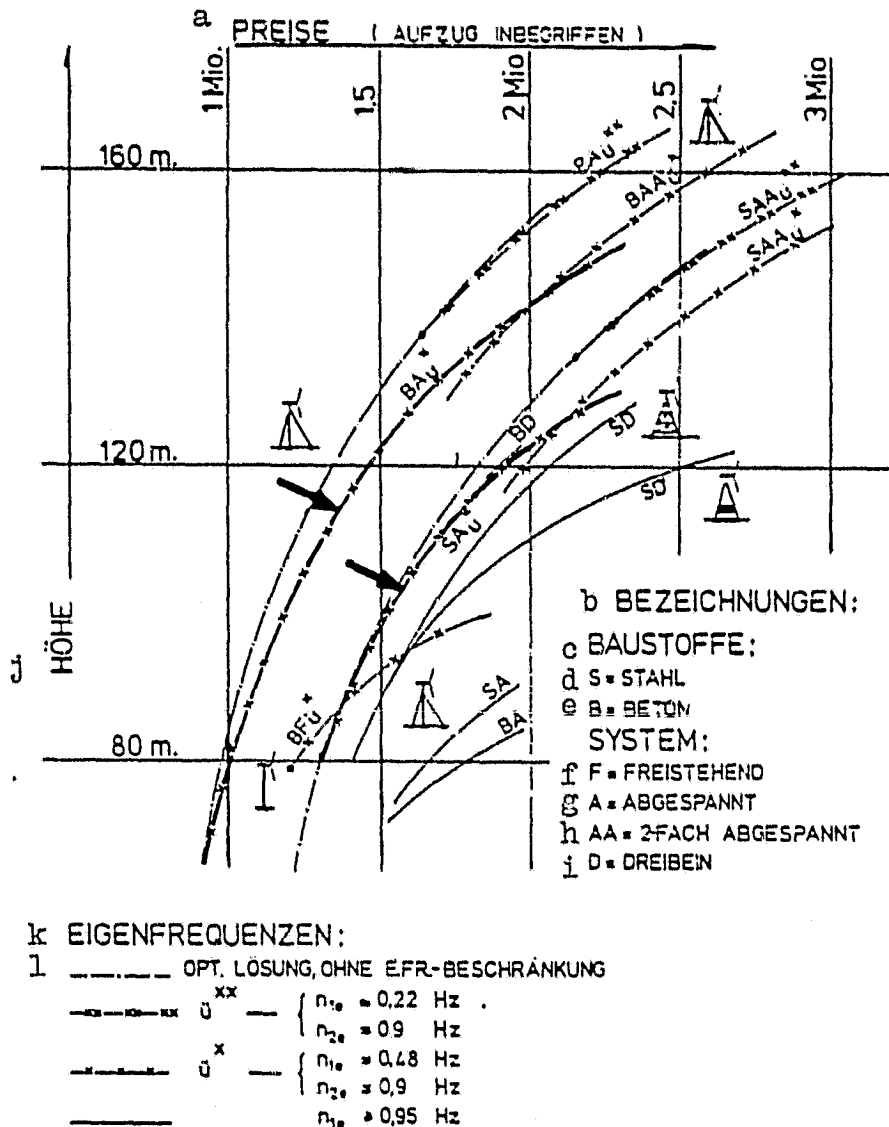
Figure 15: Longitudinal Forces and Thrust Flow in a Shaft Cross-Section

- Key:
- a. Scales
 - b. Beam force
 - c. Pressure
 - d. Tension

^a Eigenfrequenz $f \text{ s}^{-1}$	Form
1,38	b1. Schlagbiegung
1,87	c1. Schwenkbiegung
3,25	b2. Schlagbiegung
5,68	c2. Schwenkbiegung
5,93	b3. Schlagbiegung
10,18	b4. Schlagbiegung
11,65	c3. Schwenkbiegung
13,07	d1. Torsionsform
15,38	b5. Schlagbiegung
19,76	c4. Schwenkbiegung

Figure 16: Inherent Frequencies of Steel Rotor Blade
(Variant B) with CFK Blade Tip

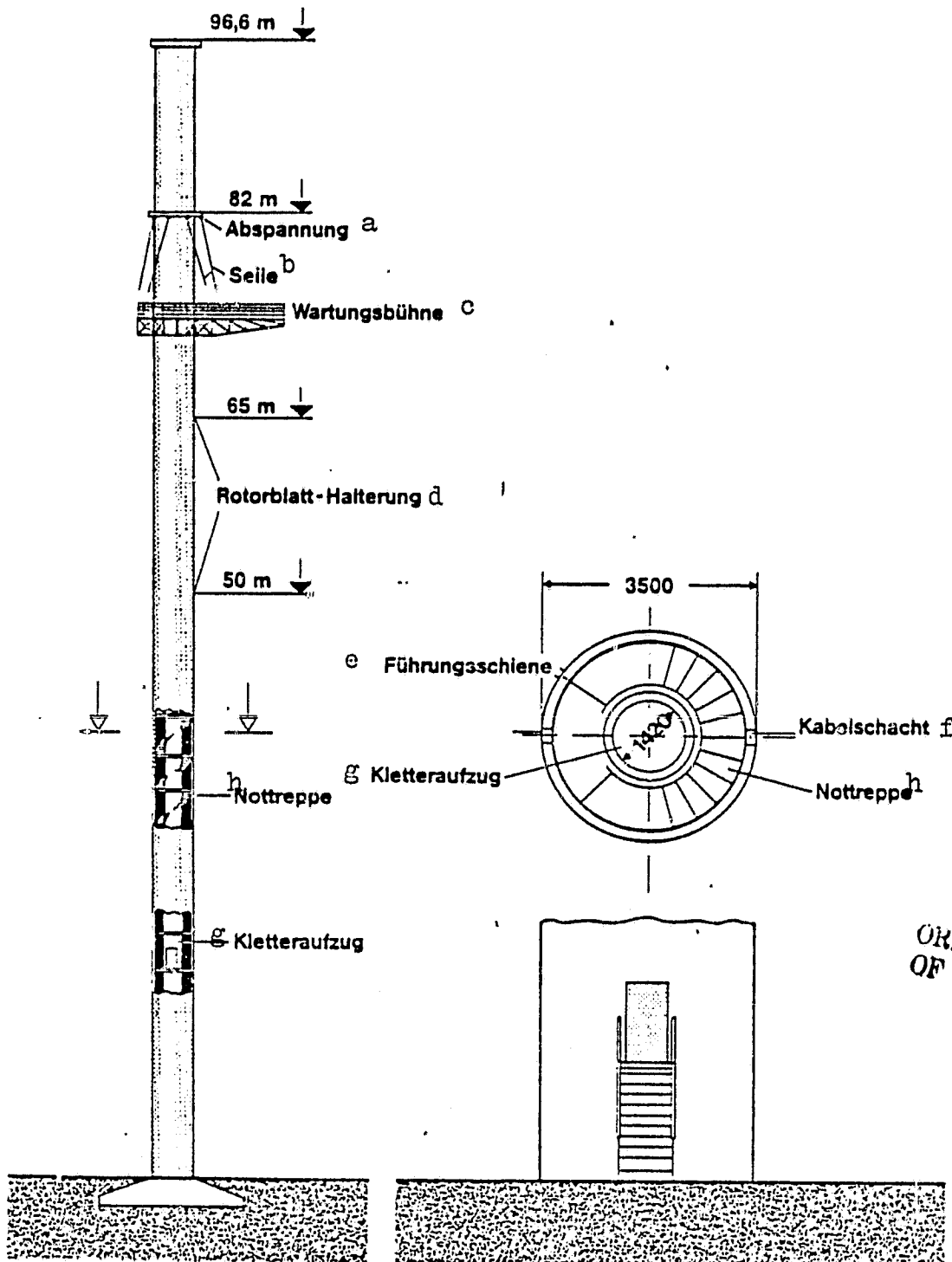
Key: a. inherent frequency
b. impact bending
c. pivot bending
d. torsion form



- Key:**
- a. Price (including elevator)
 - b. Symbols
 - c. Building materials
 - d. Steel
 - e. Cement
 - f. Free-standing
 - g. With stays
 - h. With double stays
 - i. Three-legged
 - j. Height
 - k. Inherent frequencies
 - l. Optimal solution, without limitations on inherent frequencies

Figure 17: Tower Choices

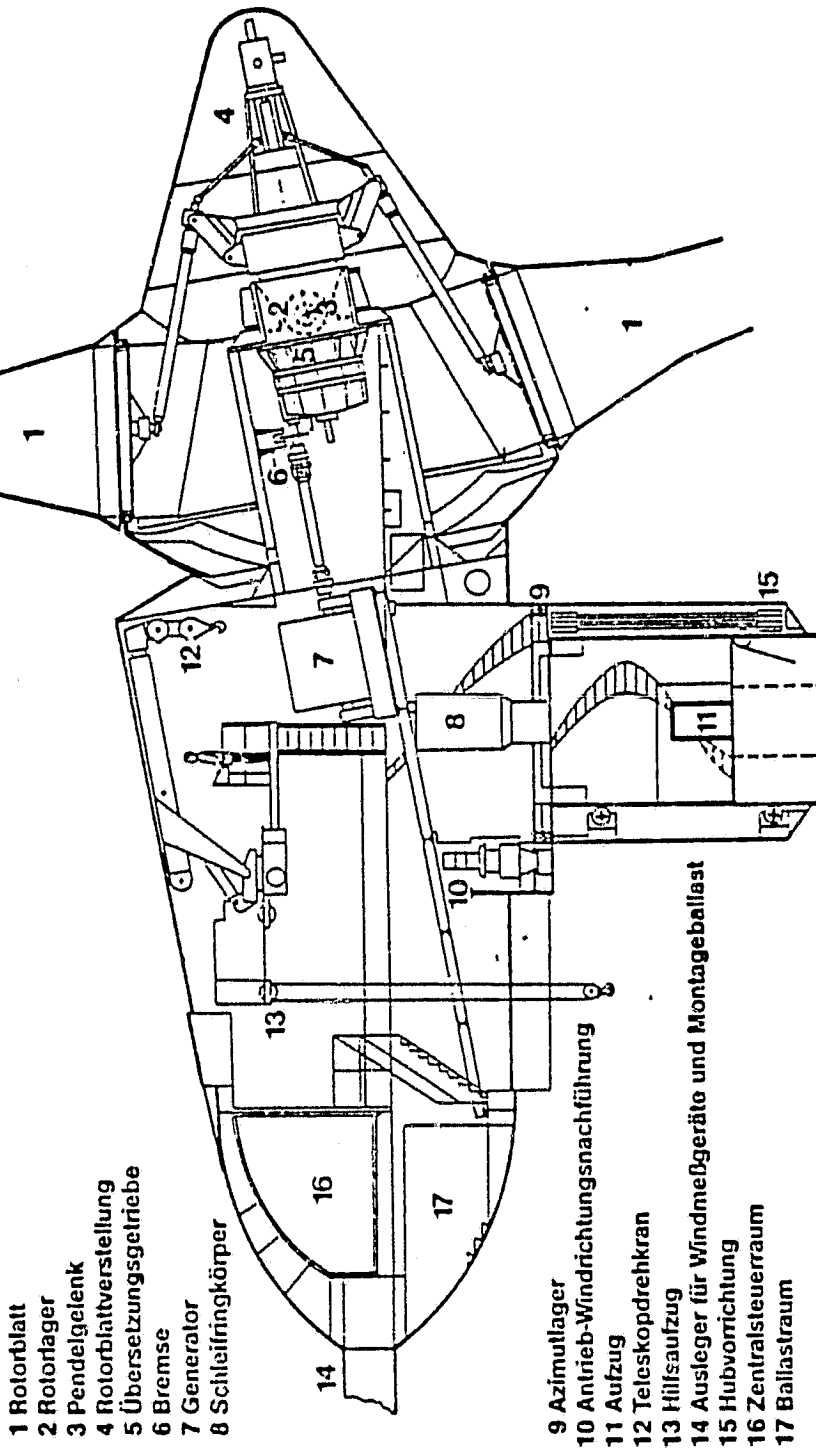
→ selected variations



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Figure 18: Tower

- | | | |
|------|-------------------------|----------------------|
| Key: | a. Stays | f. Cable shaft |
| | b. Cable | g. Climbing elevator |
| | c. Maintenance platform | h. Emergency stairs |
| | d. Rotor blade mounting | |
| | e. Guide tracks | |



- 1 Rotorblatt
- 2 Rotorlager
- 3 Pendelgelenk
- 4 Rotorblattverstellung
- 5 Übersetzungsgetriebe
- 6 Bremse
- 7 Generator
- 8 Schleifringkörper

- 9 Azimutlager
- 10 Antrieb-Windrichtungsnachführung
- 11 Aufzug
- 12 Teleskopdrehturm
- 13 Hilfsaufzug
- 14 Ausleger für Windmeßgeräte und Montageballast
- 15 Hubvorrichtung
- 16 Zentralsteuerzimmer
- 17 Ballastraum

Figure 19: Machinery Housing

- Key:
- 1. Rotor blade
 - 2. Rotor Bearing
 - 3. Swivel joint
 - 4. Rotor Blade adjustment
 - 5. Transmission gearing
 - 6. Brake
 - 7. Generator
 - 8. Slipring
 - 9. Azimuth bearing
 - 10. Drive for wind direction guidance
 - 11. Elevator
 - 12. Telescope rotary crane
 - 13. Auxiliary elevator
 - 14. Beam for wind measurement and assembly
 - 15. Lifting equipment
 - 16. Central control room
 - 17. Ballast space

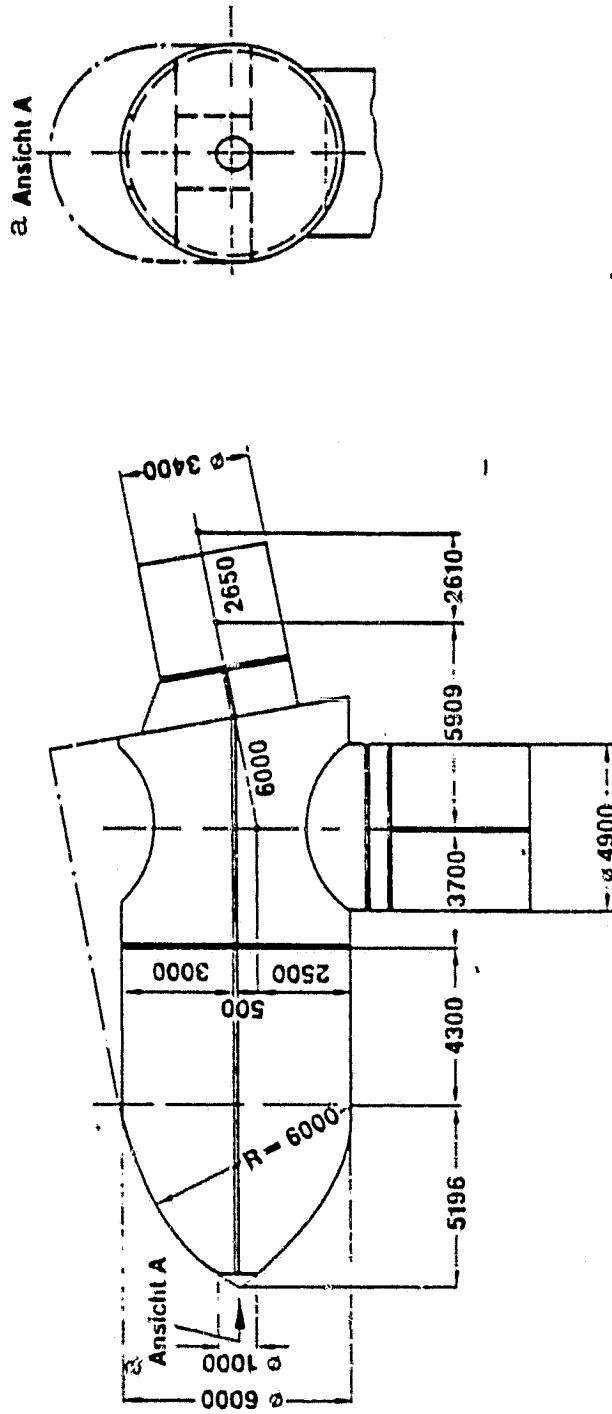


Figure 20: Structure of the Machinery Housing

Key: a. View A

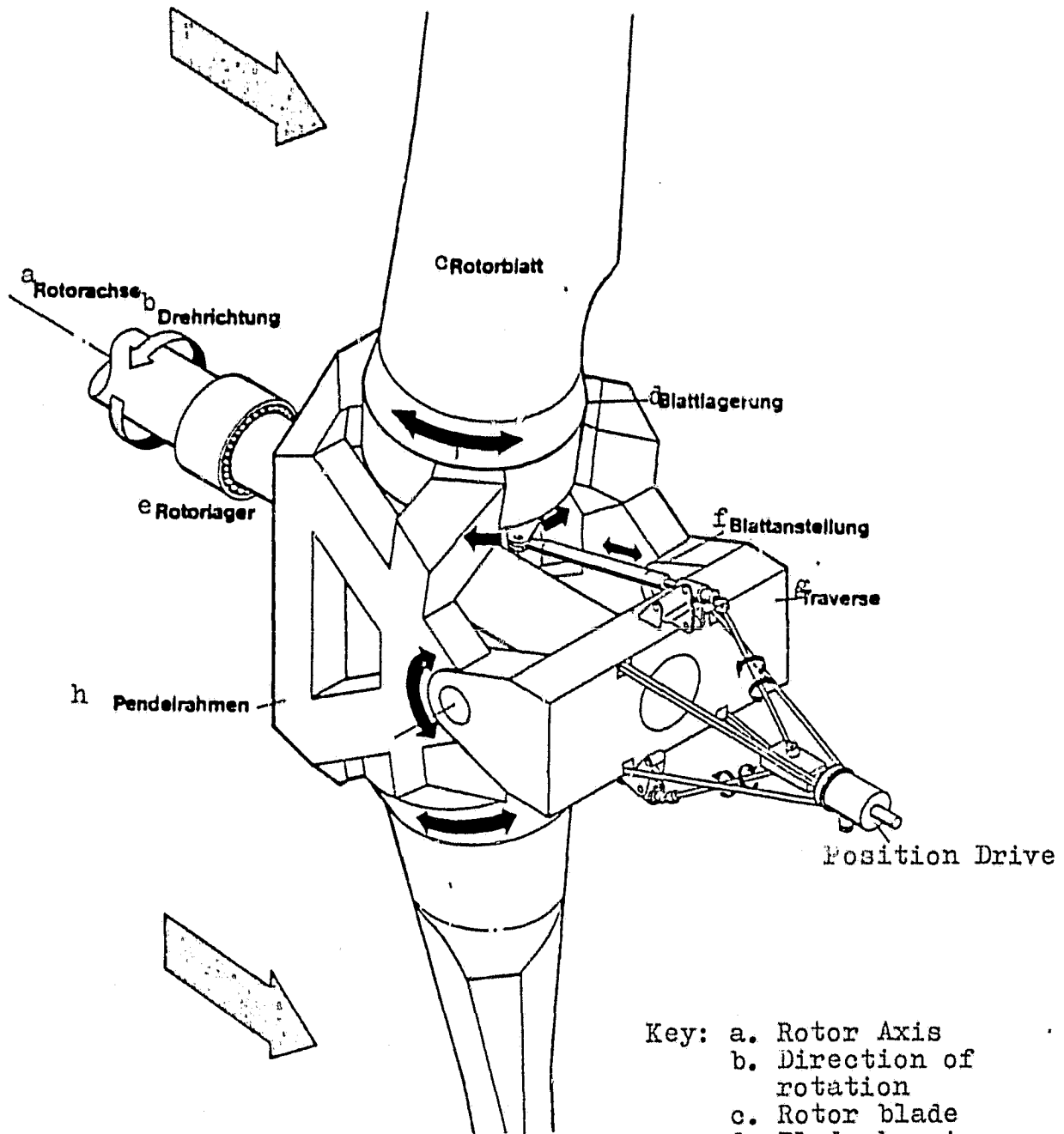
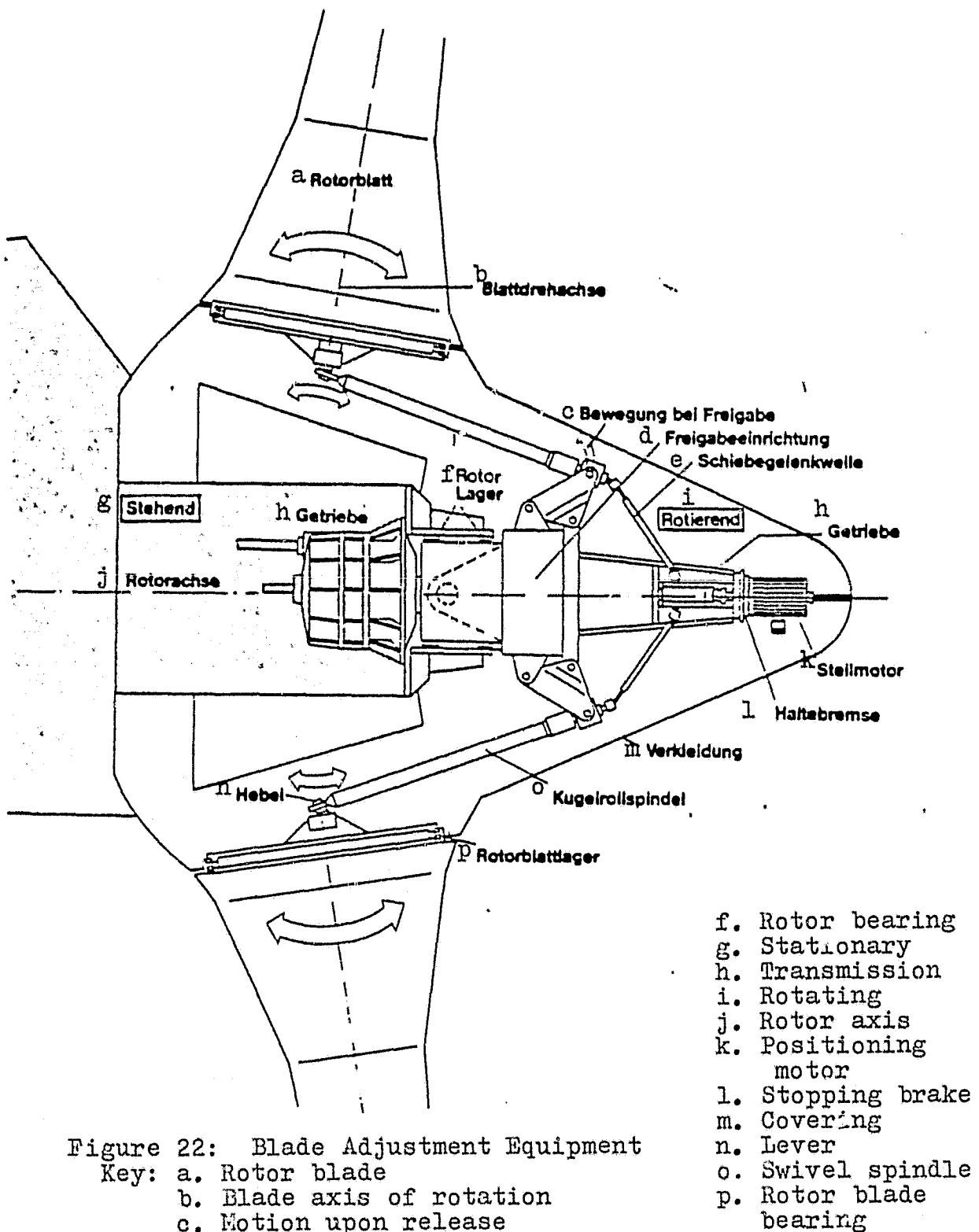


Figure 21: Cradle Hub

- Key:
- a. Rotor Axis
 - b. Direction of rotation
 - c. Rotor blade
 - d. Blade bearing
 - e. Rotor bearing
 - f. Blade adjustment
 - g. Cross beam
 - h. Swivel frame



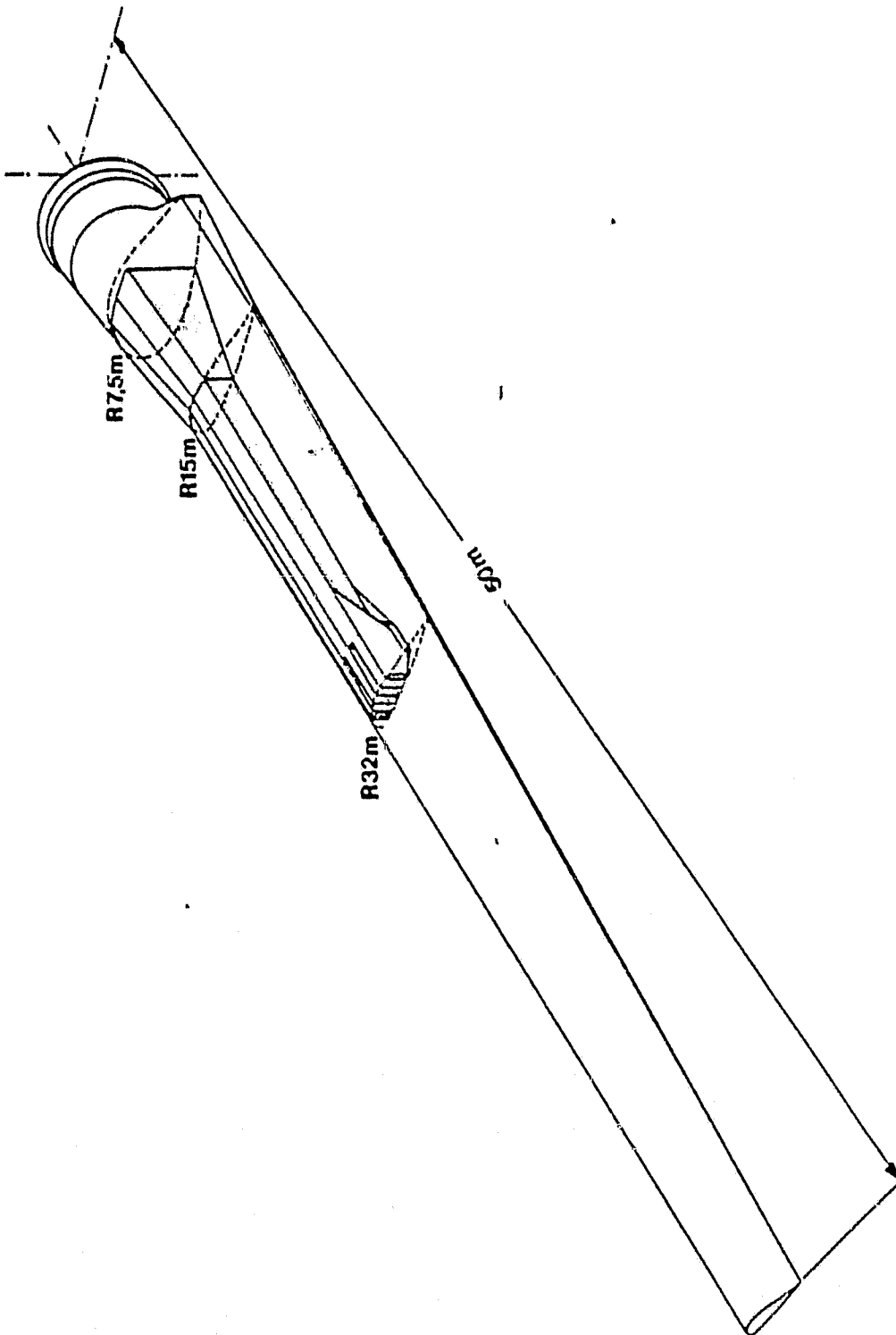


Figure 23: Rotor Blade with Steel Shaft and Blade
Tip of Reinforced Material

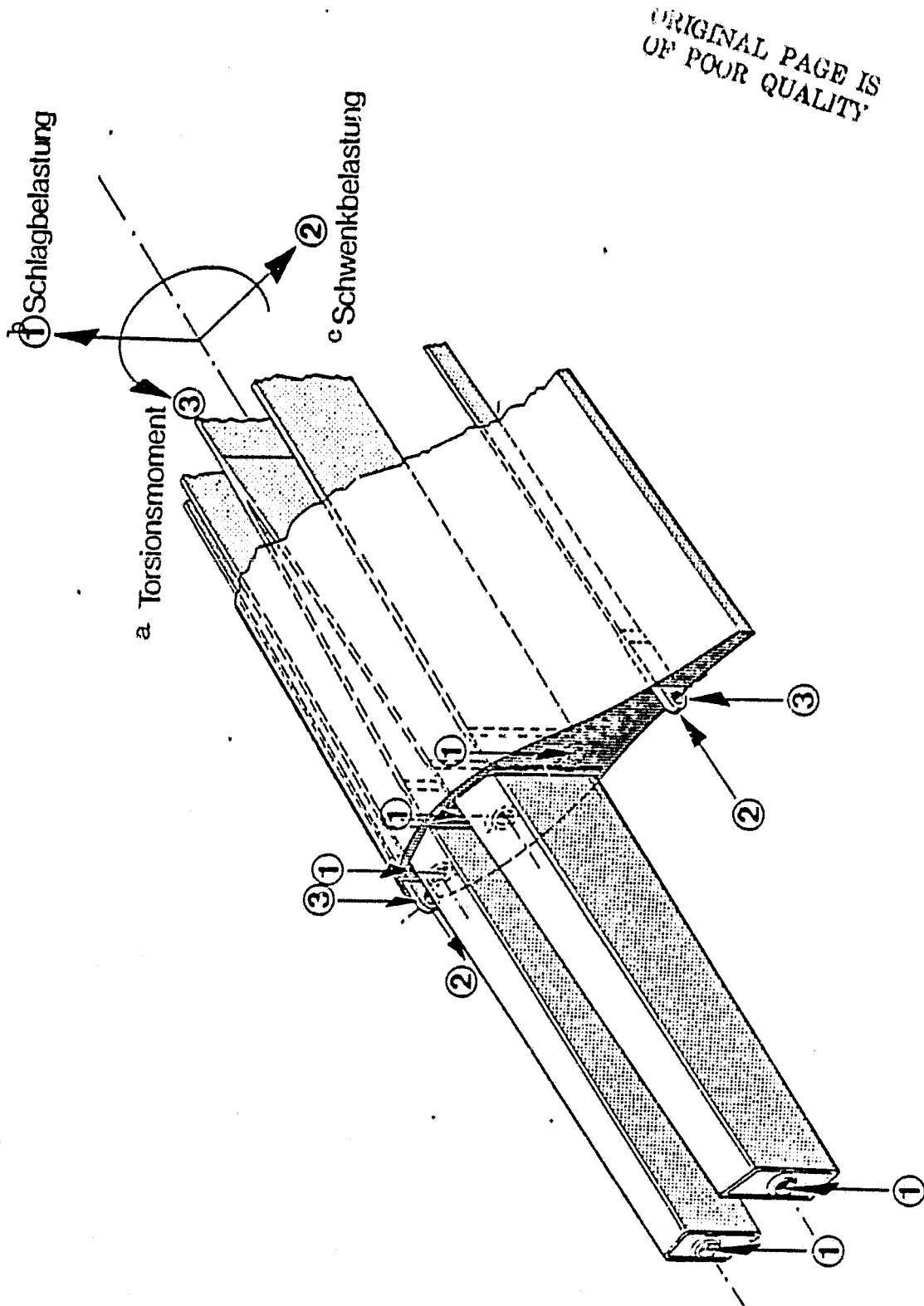


Figure 24: Distribution of Forces in the Tongue-Fork Connection of the Rotor Blade

Key: a. Torsion moment b. Impact load c. Pivotal load

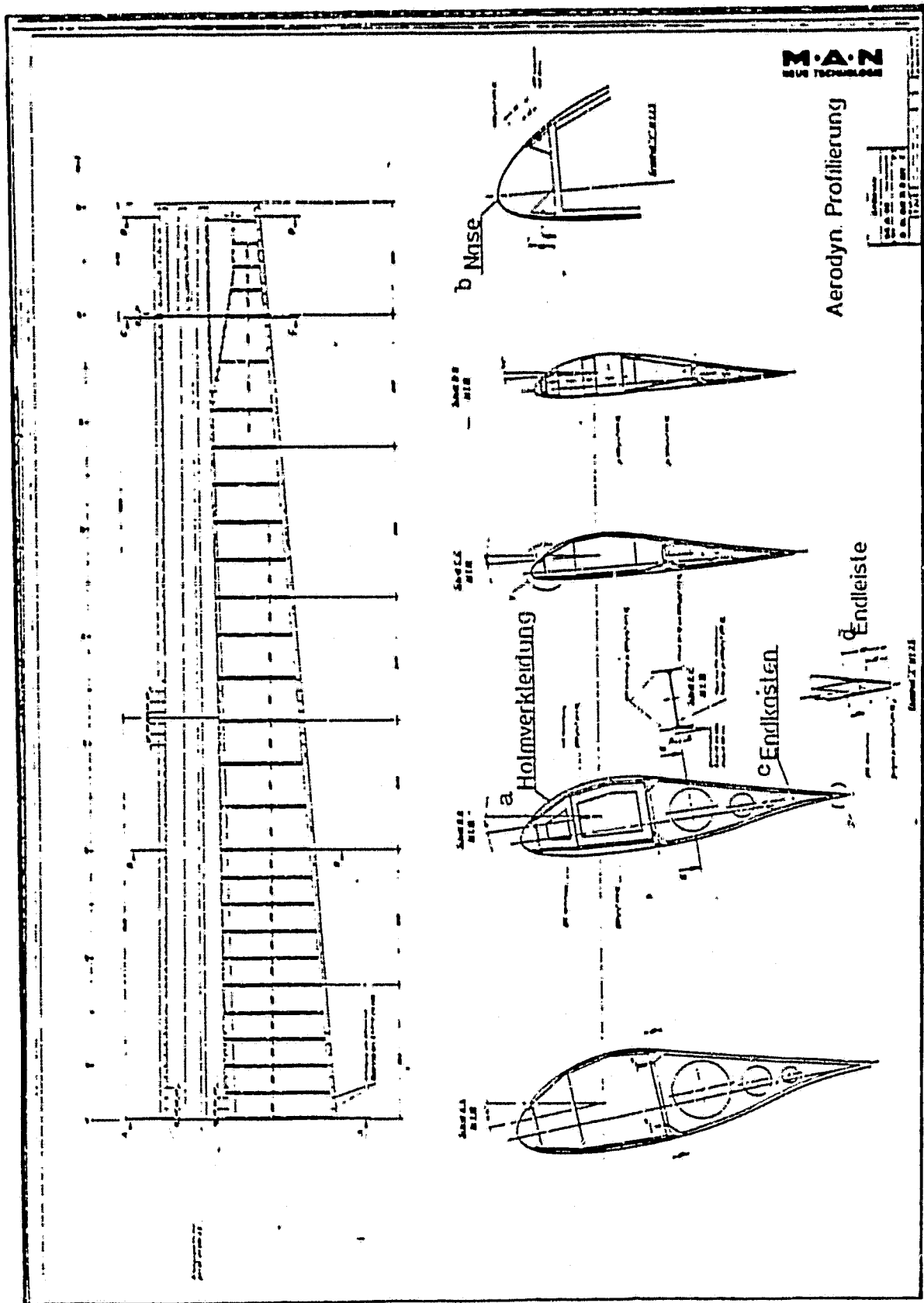


Figure 25: Aerodynamic Profiles

Key: a. Shaft covering b. Nose c. End casing d. End strip

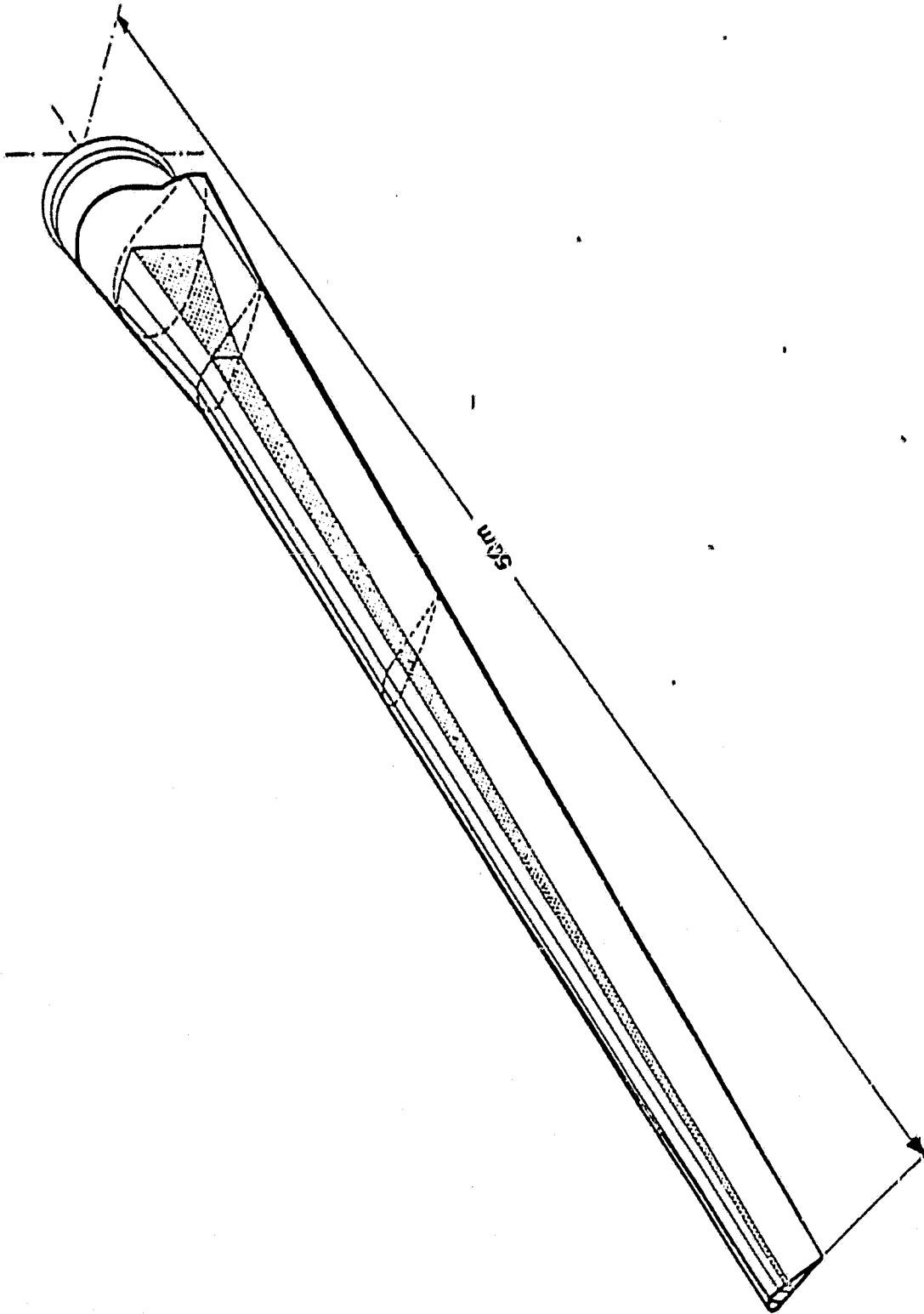


Figure 26: Steel Shaft Rotor Blades

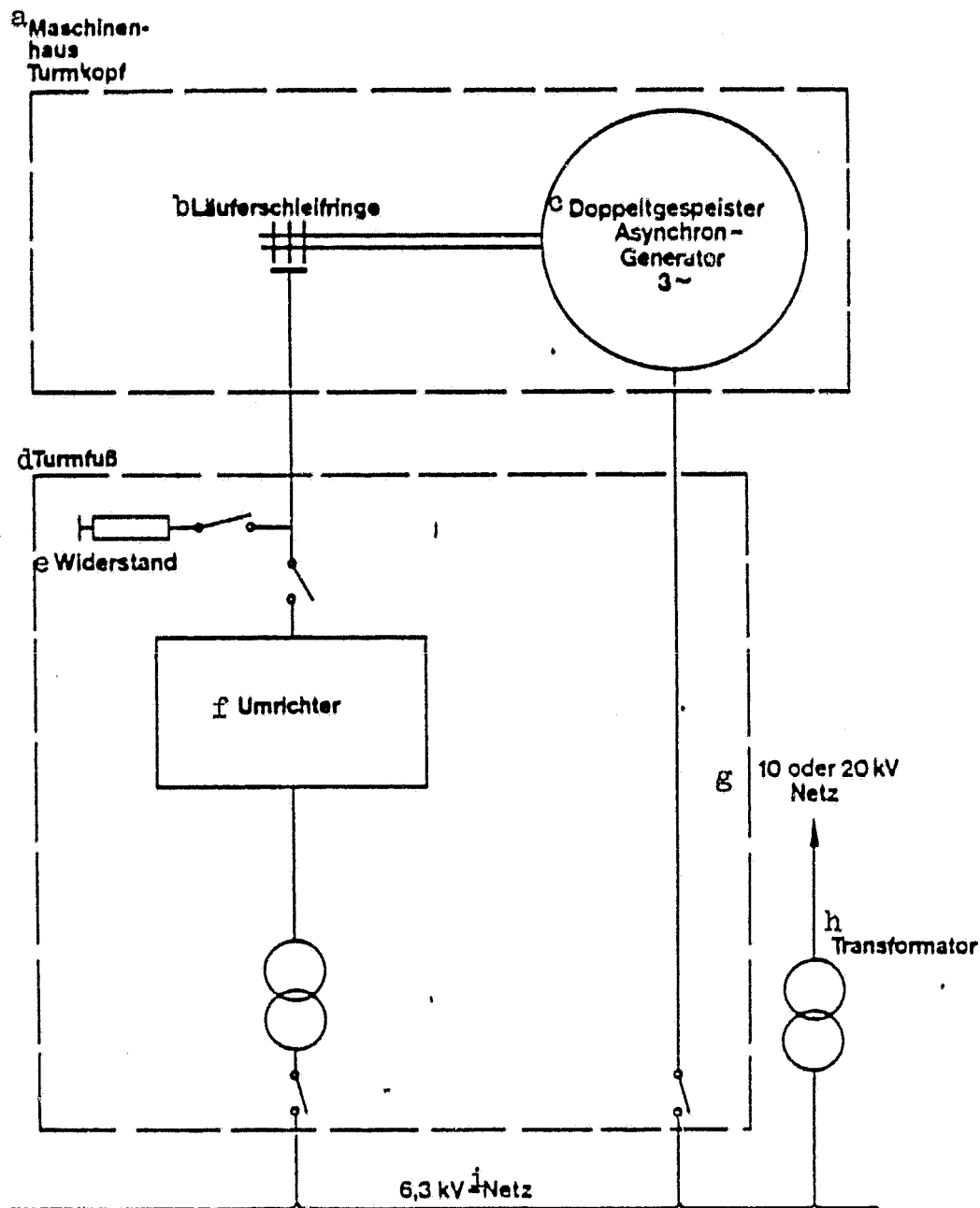


Figure 27: Diagram of Generator and System Feed

- Key:
- a. Machinery housing, tower head
 - b. Rotor sliprings
 - c. Double fed asynchronous generator
 - d. Tower base
 - e. Resistance
 - f. Frequency converter
 - g. 10 or 20 kV system
 - h. Transformer
 - i. System

1. a) Montage 1. und 2. Schuß mit Motorkran
b) Stoffnetz schweißen
2. a) Aufsetzen von Abspannung, Hubvorrichtung und Maschinenhaus mit Motorkran
b) Aufsetzen des 3. Schusses mit Motorkran
c) Verschrauben des Montage-Stosses
3. a) Aufziehen der weiteren Schüsse mit Motorkran und Verschrauben der Stöße
4. a) Aufsetzen der Hubvorrichtung mit Motorkran
b) Schweißen sämtlicher Montage-Stöße
c) Entfernen der Arbeitsgeräte mit fahrbarer Arbeitstafel
5. a) Anbau von Antriebs, Rotor und Flügeln an das Maschinenhaus
6. a) Einschwenken der Hubrolle in Hubvorrichtung
b) Befestigen des Montage Ballastes
c) Anheben von Maschinenhaus und Abspannung mit Abspannselle an Abspannschleife (B2.625)
d) Abspannung befestigen und Turm abspannen
e) Anheben des Maschinenhauses auf Endhöhe und anastieren

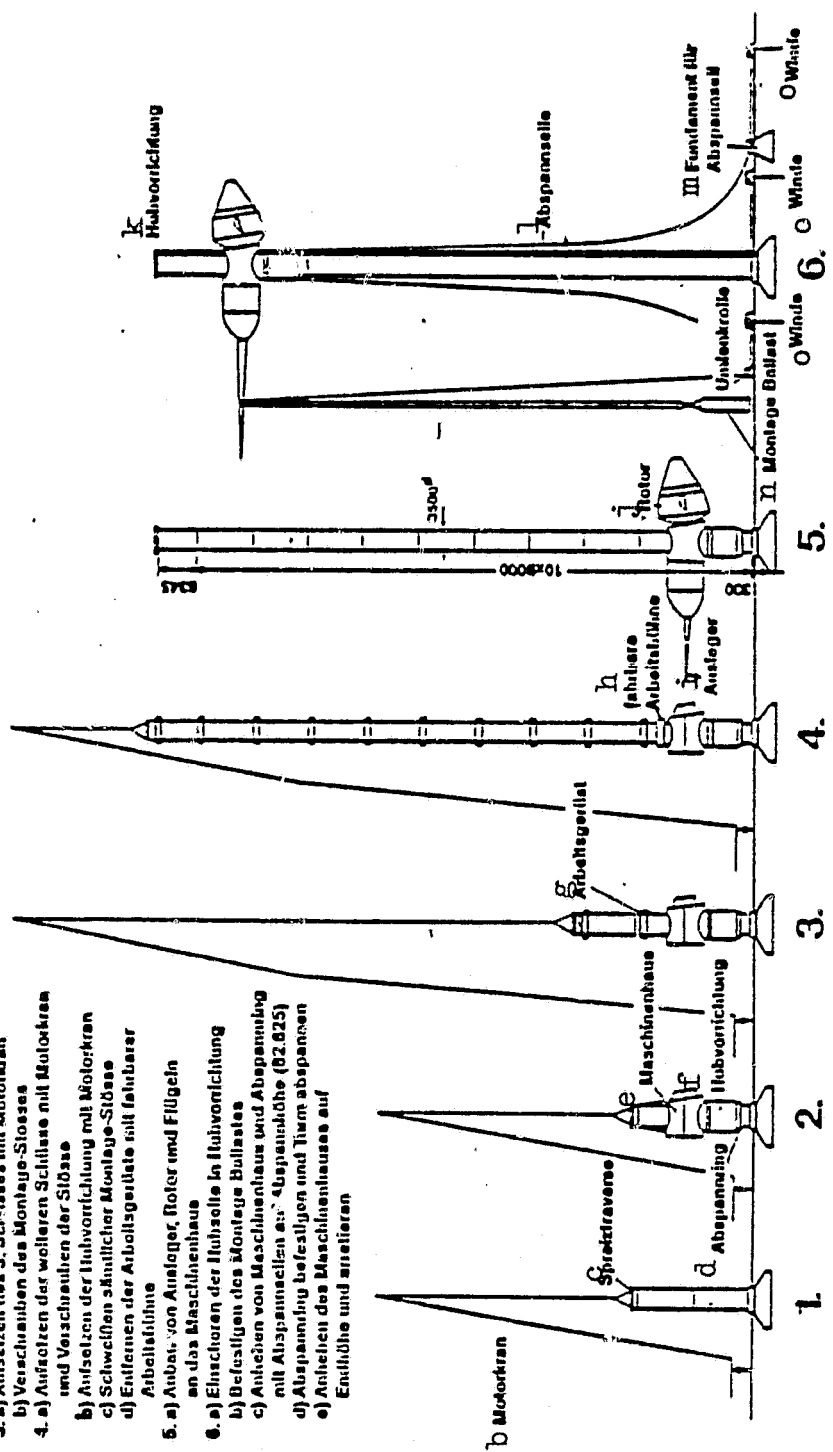


Figure 28: Tower and Machinery Housing Assembly

See following page for key.

Key for Figure 28:

- a. 1.a) Assembly of first and second sections with derrick.
b) Welding of contact seams.
 - 2.a) Positioning stay ring, lifting equipment and machinery housing torso with derrick.
 - 3.a) Positioning the third section with derrick.
b) Screwing the assembly connection.
 - 4.a) Positioning the further sections with derrick and connecting with screws.
b) Positioning the lifting equipment with derrick.
c) Welding all assembly seams.
d) Removing the scaffolding with mobile platform.
 - 5.a) Adding cross-arm, rotor and wings to the machinery housing.
 - 6.a) Moving the lifting cables into lifting position.
b) Mounting of assembly ballast.
c) Lifting machinery housing and stay ring with stay cables to the stay height (82.825 m).
d) Mounting of stay ring and final staying operation.
e) Lifting the Machinery Housing to the final position and stopping.
- b. Derrick
 - c. Straddle beam
 - d. Stay equipment
 - e. Machinery housing
 - f. Lifting equipment
 - g. Scaffolding
 - h. Mobile platform
 - i. Cross-arm
 - j. Rotor
 - k. Lifting equipment
 - l. Stay cables
 - m. Foundation for stay cables
 - n. Assembly ballast
 - o. Winch

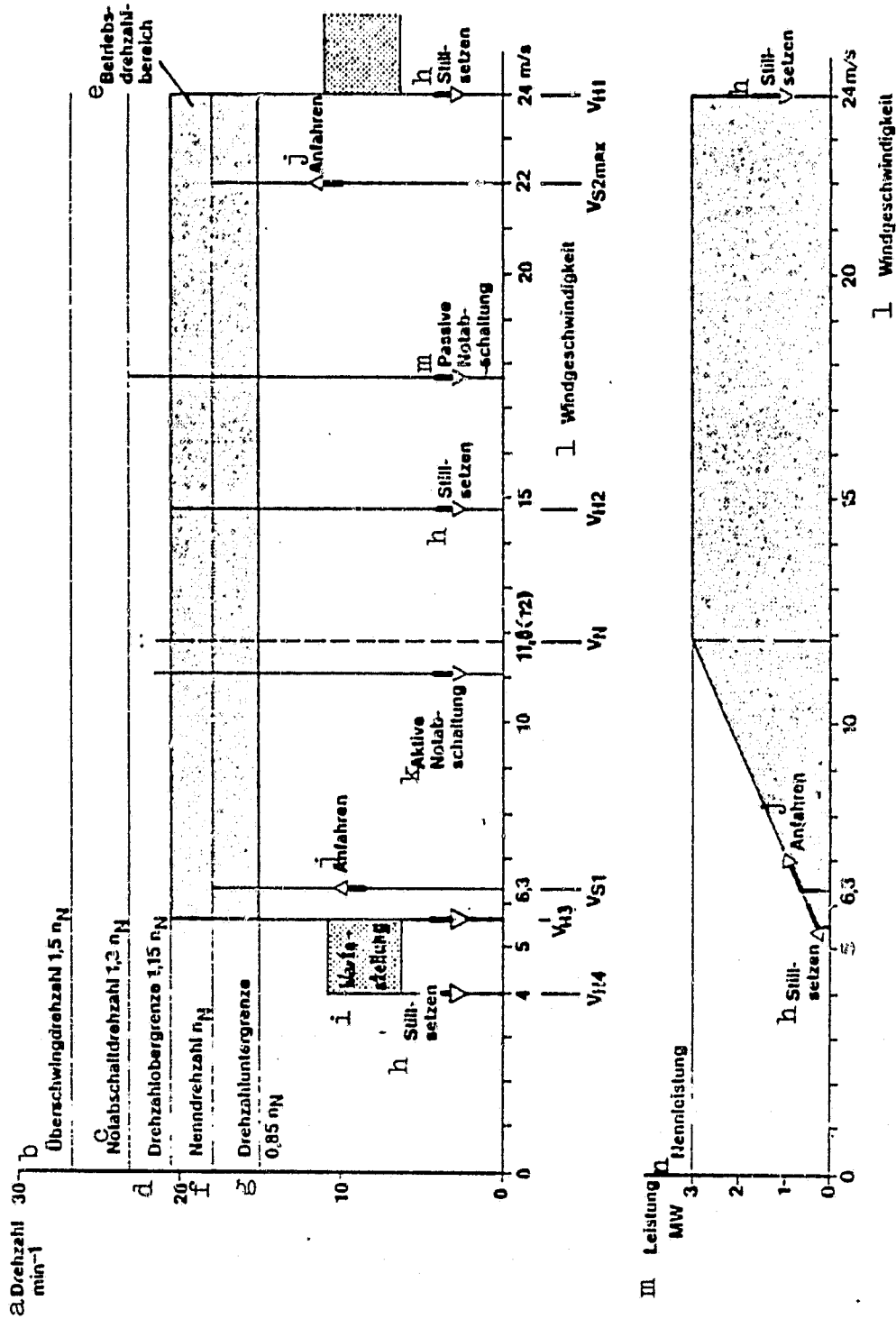


Figure 29: Cycle of Operations

- Key:
- a. Speed
 - b. Overshooting speed
 - c. Emergency switch-off speed
 - d. Upper speed limit
 - e. Operating speed range
 - f. Nominal speed
 - g. Lower speed limit
 - h. Stopping
 - i. Waiting position
 - j. Running up
 - k. Active emergency switch-off
 - l. Wind speed
 - m. Output
 - n. Nominal output

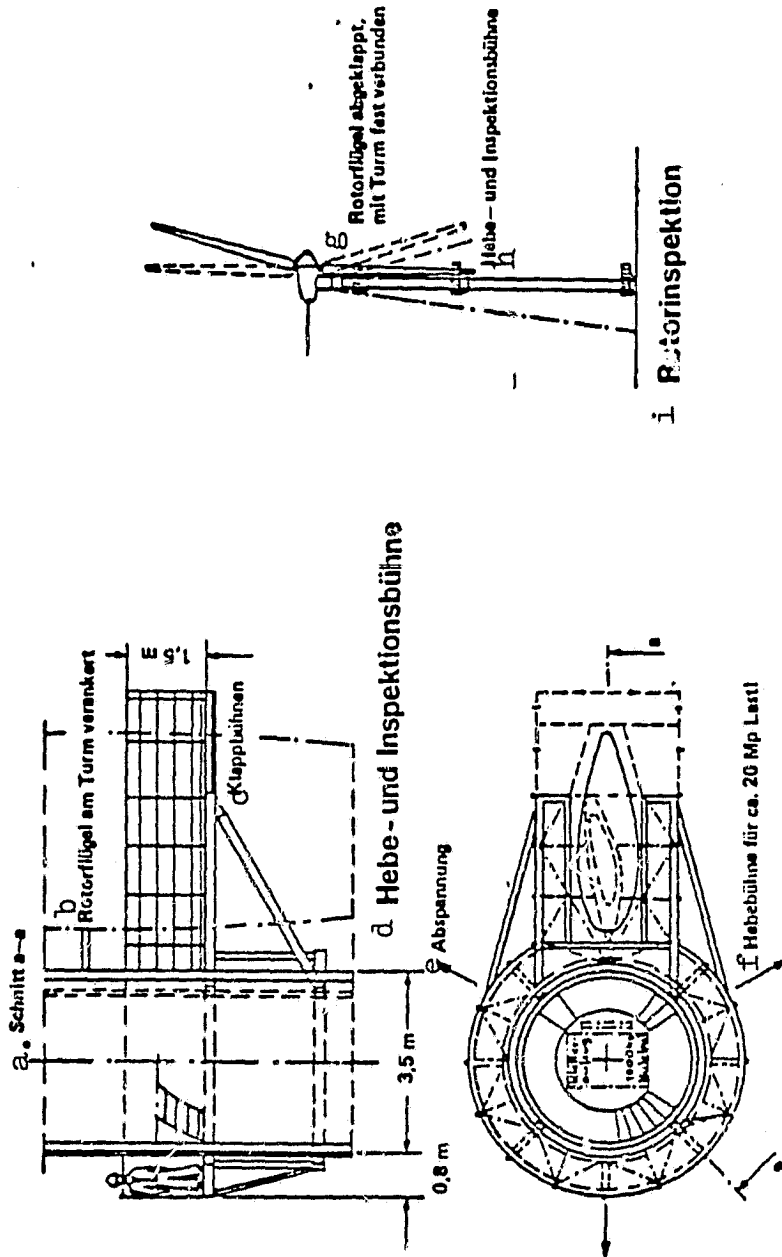


Figure 30: Rotor Maintenance and Inspection

- Key:
- a. Section a-a
 - b. Rotor wing anchored at the tower
 - c. Folding platform
 - d. Hoisting and Inspection platform
 - e. Stay
 - f. Lifting platform for approx. 20 Mp loads
 - g. Rotor blade folded down with solid connection to tower
 - h. Hoisting and Inspection platform
 - i. Rotor inspection.

Internal final reports:

M.A.N.

Final Report on Steel Tower
Dynamic Behavior of the Entire GROWIAN Plant
Final Report on Machinery Housing

DFVLR

Calculations of Structural Mechanics for the GROWIAN
Rotor Blades, Survey on the Results of the CFK-GFK Compound Wing
Internal Report IB 152-79/03

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Calculations of Structural Mechanics for the Rotor Blades with
Steel Mid-section for GROWIAN
- Configuration and Survey of the Results
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Fiber-reinforced Rotor Blade
Internal Report IB 454-79/1

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Hub Distance from the Ground
Wind Loads I and II

University in Kassel

Regulating Systems for a Large Wind Energy Plant

University in Braunschweig

Digital Reproduction of a Double-Feed Three-Phase Machine
with altering Speed, Operated at a Fixed-Frequency System

Siemens

Electrical Equipment for GROWIAN

Consulectra

Interconnected Operations of Wind energy convertors
Considerations of Profitability for the Application of Large
Wind Energy Plants

Research Institute for Wind Energy Technology

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Aerodynamic Design of the Rotor Blades for a Large Wind
Energy Converter

Leonhardt & Andrä

GROWIAN Towers - Intermediate Report
GROWIAN Towers - Final Report
GROWIAN Towers - Abbreviated Version of Final Report
GROWIAN Towers - Dynamic Design of a Medium Stiff Wind
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Accompanying Documents

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Static Calculations
March 1978

Leonhardt & Andrä

GROWIAN Reinforced Concrete Tower
Static Calculations
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M.A.N.

Calculations for Determining the Inherent Frequencies of
the Tower Construction with Stays in GROWIAN
AV, W 705 081 EGS-008

DFVLR

Calculation of the Envelop of Characteristic Curves for
Wind Rotor Performance WR 100 CFK-FXs with reduced Profile
Data
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SU-W 705 081/300

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Aerodynamic Blade Design
June 1978

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Rotor and Blade Loads for GROWIAN
WR 100 CFK-FX
Part 1 - Calculated Loads for Constant Speed of Return
Control
June 1978

M.A.N.

Studies of the Rotor Speed Behavior in the Case of
Operational Disruptions in GROWIAN
AV W 705 081-EPR 3/001

DFVLR

Problems in Calculation of Structural Mechanics in Rotor
Blades for large Wind Power Plants
IB 152-78/08

DFVLR

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Calculation of the GROWIAN Rotor Blades
June 1978

M.A.N.

GROWIAN Steel Shaft - Calculation of Strength
AV W 705 081-EGS-009
AV W 707 081-EGS-010

M.A.N.

Remarks on Proof of Strength in GROWIAN
AV W 701 011-EGS-004

M.A.N.

Screw Connections for the GROWIAN Blade Bearings
AV W 705 081-EGS-007

Prof. Nather

GROWIAN Pre-dimensioning of Cradle Hub

DFVLR

Inherent Frequency and Flutter Behavior with the Root
Torsion Stiffness as Parameter

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Studies on Lightning Protection and Design of Lightning
Protection for the Growian Rotor Blade
June 1978